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ORIGINAL ARTICLES.

The Heavy Minerals of the Plutonic Rocks of the Channel Islands: 1. Jersey.

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THE following investigation was undertaken not only with a general descriptive aim, but also to endeavour to ascertain how far correlation of isolated plutonic outcrops can be made by means of the study of the accessory minerals. It is in addition an attempt to supply further evidence bearing on the relative ages of the Jersey granites and diorites in view of the opinion of Dr. G. H. Plymen, based on field evidence, that the granites are of two ages, but both Pre-Cambrian, the Mont Orgueil and Gorey granite being the older.

Specimens were obtained from the following localities:—

"Newer" Granite: La Moye (two specimens); La Pulente, Ronez; Mont Mado (three specimens); St. Aubins (two specimens); Les Mouriers; Pontac; Longueville.

"Older" granite: Gorey (two specimens); Fort Regent (three specimens); Bathing Pool; Battery, Ronez (fine-grained edge of basic sheet); Wolf Cave, dyke in rhyolites.

Gabbro Pegmatite: Foreshore, Ronez.

Hybrid: St. Clements; The Hermitage, St. Aubins Bay.

The hybrids, which have hitherto gone under the name of diorites, were examined with a view to determining their relationship to the granites. Although, for obvious reasons, much of the magnetic material was not mounted, in all some 250 slides of grains were prepared and examined.

Method of Procedure.

The material was crushed in a special mortar and precautions were taken to minimize the formation of rock dust. Then it was passed through a thirty-mesh sieve, being afterwards washed with water to remove any rock dust and dried. It was then passed through bromoform, the grains, with the exception of the specimens of the "Older" Granites, not requiring any cleaning with acid. However, owing to the large bulk of biotite obtained in the heavy residue after passing through bromoform, it was found necessary in several cases to modify the procedure as follows:—The heavy residue was divided into two parts, one of which was submitted to an electromagnetic separation directly while the other first had its biotite removed by boiling in concentrated hydrochloric acid for about half an hour, when, after washing and drying, the baueritized biotite was completely removed by a further bromoform separation. Such minerals as would be destroyed by the acid were still represented in the other portion. Where, as in the case of the gabbros, hornblende forms 60 per cent to 70 per cent of the rock, the hornblende can be removed with a high degree of perfection by the electromagnet. In some cases a further separation was made with methylene iodide.

"NEWER" GRANITE.

List of Heavy Minerals.—The following have been observed and are listed in the approximate order of relative abundance. Hornblende, biotite, fluor, sphene, epidote, zircon, apatite, chlorite, magnetite, ilmenite,[1] clinozoisite, zoisite, molybdenite, pyrite, sillimanite, topaz, leucoxene, andalusite.

Description of Heavy Minerals.—It will thus be seen that the minerals sphene, biotite, zircon, apatite, hornblende, magnetite, and the three members of the epidote group, epidote, clinozoisite, and zoisite, are typical of these granites. Zoisite is shown by thin sections to have been formed after the main mass of the granite had consolidated, probably at a late stage of the cooling. Much of the epidote has also been formed in the same way, although in the specimen from Pontac some of it may have been derived from the decomposition of ferromagnesian minerals. There is no evidence to show whether the clinozoisite is primary or not, but it is usually regarded as of secondary origin. The abundance of fluor disseminated through the rock at Mont Mado is noteworthy. Fluorine is also in evidence in the South-West Granite as is shown by the presence of fluor and topaz. The occurrence of inclusions of apatite in fluor, and more rarely in topaz, would seem to show that much of the apatite is fluor-apatite.

Zircon.—Occurs in three main types:—

1. Colourless and transparent with pyramid faces fairly equally developed. Occasional inclusions.
2. Lightly coloured and more or less zoned and semi-turbid with inclusions. Colour: pale yellow, grey, or brown. Faces more irregularly developed.

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[1] The presence of ilmenite has in each case been confirmed by a chemical test for titanium made on the material picked up by a large horseshoe magnet.

TABLE SHOWING DISTRIBUTION OF THE HEAVY MINERALS.

LOCALITY.	No. of Specimens.	Zircon.	Apatite.	Biotite.	Hornblende.	Sphene.	Epidote.	Clinozoisite.	Titan Augite.	Zoisite.	Chlorite.	Fluor.	Magnetite.	Ilmenite.	Leucoxene.	Haematite.	Pyrite.	Molybdenite.	Topaz.	Sillimanite.	Rutile.	Olivine.	Barkevikite.	DESCRIPTION OF SPECIMENS.	Per cent of heavy minerals.
Ronez . .	1	4	4	5	5	4	3	3	–	–	3	5	4	–	–	–	4	2	–	3	–	–	–	" Newer " Granite.	8·2
Mont Mado. .	3	4	4	5	5	4	3	3	–	–	5	5	4	–	–	–	–	–	–	–	–	–	–	,, ,,	3·8
Les Mouriers .	1	4	4	5	5	3	–	–	–	–	3	–	3	3	1	–	–	–	–	–	–	–	–	,, ,,	16·8
La Moye . .	2	4	4	5	5	4	3	3	–	–	3	5	4	3	–	–	–	–	1	1	–	–	–	,, ,,	8·9
La Pulente .	1	4	4	5	5	3	3	–	–	–	3	5	4	–	–	–	–	–	–	–	–	–	–	,, ,,	5·3
St. Aubins . .	2	4	4	5	5	3	–	–	–	–	3	–	3	3	3	–	–	–	–	–	–	–	–	,, ,,	9·1
Pontac . .	1	4	4	5	–	4	5	4	–	4	5	–	3	3	1	–	1	–	–	–	–	–	–	,, ,,	6·7
Longueville .	1	4	5	5	3	4	3	–	–	–	4	–	–	–	–	–	–	–	–	–	–	–	–	,, ,,	19·7
The Hermitage .	1	4	4	5	5	3	5	3	–	–	5	–	3	–	–	–	–	–	–	–	–	–	–	Hybrid.	48
St. Clements .	1	4	4	5	5	5	5	3	–	3	5	–	4	3	–	–	3	–	–	–	–	–	–	,,	51
Batt. Ronez .	1	4	4	5	5	5	4	1	–	3	5	–	3	–	–	–	–	–	–	–	–	1	5	Gabbro.	53
Ronez . .	1	3	4	4	4	3	4	–	3	–	4	–	3	3	–	–	5	–	–	–	1	–	4	Gabbro Pegmatite.	29·5
Wolf Cave . .	1	1	3	5	5	4	4	–	5	5	5	–	3	3	–	–	–	–	–	–	1	5	4	Olivine Gabbro.	69·8
Gorey . .	2	3	–	3	–	1	–	–	–	–	3	–	4	–	–	4	–	–	–	–	–	–	–	" Older " Granite.	0·21
Fort Regent .	3	3	2	–	–	–	–	–	–	–	3	–	3	–	–	4	–	–	–	–	–	–	–	,, ,,	0·9
Bathing Pool .	1	3	2	–	–	–	–	–	–	–	3	–	3	–	–	4	–	–	–	–	–	–	–	,, ,,	0·8
Pen Voose . .	2	3	4	3	–	–	–	–	–	–	3	–	4	–	–	–	–	–	–	–	–	–	–	Granite Gneiss.	0·39

5 = Abundant. 4 = Common. 3 = Less common. 2 = Scarce. 1 = Rare.

3. Almost or quite opaque with inclusions and having faces often very unequally developed. Resorbed forms are very rare (cf. Lizard and "Older" Granite). Some few bent crystals have been observed and also a few cases of two crystals in parallel growth. The unit pyramid is the only one which has been observed. The length of the crystals may be anything up to ·35 mm., but the average is about ·15 to ·25 mm.

Apatite.—The usual prism capped by pyramid and basal plane, but in the majority of cases the terminations are not to be seen owing to the basal parting. Crystals having a central core of inclusions are extremely common, and these usually show slight absorption when the light from the polarizer is vibrating parallel to the vertical axis. A few cases have been noted where apatite grains have shown distinct pleochroism from grey to blue accompanied by a more appreciable difference of absorption.

Fluor.—Occurs in colourless grains showing occasional purple blotches, and having a conchoidal fracture. Some of the larger grains in the granite of La Moye contain good inclusions of apatite showing the cross fracture or basal cleavage and these are presumably fluor-apatite. Anomalous B.R. is practically absent. Prolonged search has failed to reveal the presence of any garnet.

Sphene.—This mineral is very variable in colour ranging from a very pale brown to dark brown, and rich shades of golden brown. Occasionally it may be nearly green or yellow.

Clinozoisite.—Occurs in broken stumpy prismatic crystals having extinction angles up to 30°. Between crossed nicols this mineral is readily picked out in any field on account of the beautiful ultra-blue polarization colours. The largest fragments observed are ·25 mm. along the b axis, but these probably represent much larger crystals.

Hornblende.—Owing to the deep colour of this mineral all but the very thin cleavage flakes are practically opaque. The pleochroism is strong and ranges from straw yellow to a very deep brown, and from a brownish-green to a deep bluish-green.

Biotite.—Very deep brown. Baueritization takes about thirty minutes to perform. Pleochroic haloes common.

The evidence afforded by the heavy residues from the preceding specimens of granite is most strongly in favour of the view that these granites are of the same age, for the residues are closely similar both as regards the characters of the minerals and the mineral species.

Comparison of the "Newer" Granites with the Armorican Granites of the West of England.—The minerals of frequent occurrence and common to both are zircon, apatite, and biotite, while sphene is common in Jersey but inconstant on Dartmoor.

Our knowledge of the minerals of these granites, and of Dartmoor in particular, is extensive, thanks to the recent work of several investigators.[1] The granites of Jersey are not so very far distant from the Armorican granites of the West of England, and it is natural for suggestions to be made to the effect that the two are contemporaneous.[1] If such were the case then we should expect a strong resemblance in the heavy mineral suites, but no such resemblances are to be found; on the contrary there are great differences as the following comparison shows. The chief heavy minerals of the Dartmoor Granite are:—Tourmaline, biotite, ilmenite, garnet, zircon, apatite, cassiterite, anatase, rutile, brookite, muscovite, and monazite. Those of the Jersey granites so far considered are:—Hornblende, biotite, fluor, sphene, zircon, apatite, magnetite, chlorite, epidote, zoisite, and clinozoisite. Tourmaline is by far the most abundant mineral (apart from quartz and felspar) in the West of England Armorican granites, and yet not a single crystal of it has been observed in the residues from Jersey granites. Muscovite and garnet are two other minerals common in the one and absent in the other. Some of the most typical of Dartmoor minerals are monazite, anatase, rutile, and brookite, all of which are absent from the Jersey granites. Again, the most abundant heavy mineral in the Jersey granites with the exception of biotite is hornblende, yet on Dartmoor hornblende occurs only in some included blocks of hornfelsed greenstone.

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[1] A. Brammall, *Proc. Geol. Assoc.*, vol. xxxvii, 1926, p. 251; *Min. Mag*, vol. xx, 1923.

The differences pointed out in the last paragraph have considerable weight and denote differences in the composition of the magmas especially as regards the minor constituents. Thus from the point of heavy minerals there appears to be no genetic relationship between the Armorican granites of the West of England and the "Newer" Granite of Jersey, and this may be taken as evidence that the latter are not Armorican in age.

"OLDER" GRANITE.

Gorey Granite.—It was found that this contained a very low percentage of heavy minerals and a large quantity of rock had to be crushed in consequence.[2] Not only is the percentage of heavy minerals much lower than in the other Jersey granites, but the crystals themselves are also small, requiring a magnification of three hundred diameters for their examination, with the exception of magnetite.[3]

Zircon.—The majority of the zircons are coloured in some shade of brown or yellow and are frequently very corroded. At the same time there are some slightly larger colourless zircons containing many large and irregularly arranged inclusions. The coloured zircons are for the most part cloudy while the colourless ones are clear. Length: ·05 to ·1 mm.

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[1] Hatch and Wells, *Text-book of Petrology*, vol. i, p. 433.

[2] The amount of rock crushed in the case of each specimen was never less than about a quarter of a pound; in exceptional cases five or six times this quantity was crushed.

[3] For the complete list of minerals from each locality refer to the table.

Sphene.—A practically colourless variety. Identified by its high R.I., strong B.R., strong dispersion, and by the fact that it never quite extinguishes.

Magnetite.—Abundant and occurring in perfect octahedra.

Fort Regent Granite.—Specimens of the Fort Regent granite taken from around the fort, and one from the rocks exposed at low water near the bathing pool, gave a suite of accessory minerals which, apart from the presence of apatite, was identical with that of the Gorey granite. The two types of zircon in the one can be matched with those in the other, including the dimensions of the crystals and their frequently observed corroded character. In the hand specimen the Fort Regent granite resembles the Gorey granite, but is of finer texture. The nature of the outcrop of the Fort Regent granite suggests[1] intrusion from a southerly direction, and it is very probable that the rocks running out to the Dogs Nest, etc., also belong to this granite.

Comparison of the "Older" Granite with the "Newer" Granite.—Comparison of the heavy minerals of the Gorey and Fort Regent granite masses with those of the other Jersey granites shows many differences, the chief of which are :—

(*a*) Absence of clinozoisite, zoisite, epidote, and hornblende from the "Older" Granite.

(*b*) Great paucity of biotite in the "Older" Granite.

(*c*) The zircons differ in character.

(*d*) The percentage of heavy minerals is much lower than that of the "Newer" Granite.

Comparison of "Older" Granite with Granite Gneiss of the Lizard.—Both rocks yield an extremely small residue of heavy minerals, that of the Lizard being 0·39 per cent (largely made up of biotite), while that of the Gorey granite is 0·21 per cent and that of Fort Regent is of the same order. In either case a pound of rock will scarcely yield sufficient non-magnetic material to make a full slide using a seven-eighths of an inch square cover glass. The actual crystals in the Lizard material are about the same size as in the Gorey granite, both requiring the continual use of a quarter inch objective for their examination. The amount of biotite is about the same in both and compared with the "Newer" Granite is extremely small in amount. The paucity of minerals reduces the species available for purposes of comparison to zircon, apatite, and magnetite. The zircons of the Gorey granite are grey, greyish-brown, or have yellowish patches and are frequently ovoid in shape and the majority are devoid of crystal faces as a result of corrosion. In the Lizard material the majority of the zircons are corroded and many of them can be matched as regards colour and shape with those from Gorey. Although apatite is common in the Granite Gneiss of the Lizard it is absent from Gorey. However, the whole of the Gorey mass is reddened with iron staining and much altered, and it seems in this case quite feasible to suppose that any apatite which may have existed has been dissolved out. Decomposition of small quantities of pyrite would introduce a powerful acid leaching factor. The reddening of the Gorey granite may be also due to hydrothermal action, in fact, this is the more probable in view of the proximity of granite porphyry intrusions and the probable extrusion of lavas in the vicinity.[1] The apatite of the "Older" Granite and of the Granite Gneiss of Pen Voose does not contain any of the central rod-like inclusions, accompanied apparently by slight difference of absorption, which is a characteristic of the "Newer" Granite. Both in the Granite Gneiss and in the Gorey granite magnetite occurs in perfectly formed octahedra. The "Older" Granite is not foliated, and much of the Granite Gneiss of the Lizard shows but little foliation.

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[1] G. H. Plymen, *Proceedings Geologists' Association*, xxxiii, 1921, p. 166.

It will thus be seen that the correlation in this case is dependent as much on the absence of heavy minerals as by their presence, nevertheless, the resemblance between the two suites is very marked. However, as is always the case with heavy minerals, the correlation is more convincing after an examination of the slides than the perusal of a written description can ever hope to be.

The older granite of the Lizard—the Man o' War Gneiss—has suffered very considerable metamorphism and is now a hornblendic gneiss, and inasmuch as its mineralogical composition has no doubt been largely reconstituted, comparisons with it were not considered feasible.

If we accept a Pre-Cambrian age for the Granite Gneiss of the Lizard then the heavy mineral evidence points to a Pre-Cambrian age for the "Older" Granite; but the Granite Gneiss is the last of the great cycle of intrusions in the Lizard, so that the question arises as to whether the "Newer" Granite of Jersey is of later Pre-Cambrian age or later still.

THE MORE BASIC ROCKS.

The rocks which have been hitherto known as diorites in Jersey have been shown by the contemporary work of Dr. Wells and Mr. Wooldridge to be, in the Ronez district, of a hybrid nature, and they maintain that these rocks are the result of assimilation by the "Newer" Granite of a basic rock of a gabbroid nature. Owing to the variable nature of these hybrid rocks it has been thought advisable to include a short petrological description of each of the specimens used in order that the reader may have a clear idea of the character of the material used.

Gabbro: Battery, Ronez.—Abundant hornblende, with largely chloritized biotite, and kaolinized felspar, showing intersertal structure on a scale much coarser than that displayed by a dolerite, make up the bulk of the rock. In addition calcite, sphene, and magnetite are the most important accessory minerals, while granular epidote, minute apatite, and some secondary quartz also occur. In places there is a marked ophitic tendency. Some of the patches of chlorite display the form of augite, and penetrating them are laths of felspar. A certain proportion of the hornblende is very likely to be derived from former pyroxene. No primary quartz is present. The numerous patches of calcite, epidote, and chlorite also point to the probable former presence of augite. There is much water-clear secondary albite, but the nature of the original felspar cannot be determined, but is probably labradorite. The rock is thus an altered gabbro, and the use of the term epidiorite seems appropriate.

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[1] It should be noted that apatite is present in the Fort Regent mass.

The heavy residue from this rock formed 53 per cent of the whole, of which whole 51 per cent was hornblende and chloritized biotite. The bromoform separation in such a case requires great care in manipulation. It was found that the best separation was obtained by the use of a very large funnel which gave a large surface of bromoform on to which the crushed rock was lightly and evenly scattered from the blade of a penknife, but the method is rather slow. The accessory minerals were found to be very different in character from those of both the " Newer " and the " Older " Granite and so the gabbro is presumed to be intermediate in age.

Description of the Heavy Minerals of the Gabbro: Sphene.—Generally pale in colour and on the whole paler in colour than the sphene of the " Newer " Granite. Owing to the good cleavage smashes into jagged fragments and crystal faces are rarely to be observed. In such a case useful figures concerning the dimensions of the crystals cannot be given from the heavy residues, but in the case of sphene a rough idea may be obtained by reference to several thin sections. Forms a flood in the non-magnetic portion of the residue.

Zircon.—Occurs in two types :—

1. Very elongated narrow colourless crystals up to ·5 mm. in length.

2. Larger and fatter crystals having a slight pinkish-grey tint frequently showing vertical striations and sometimes vertical rod-like inclusions. The length of the crystals varies from ·5 mm. to ·7 mm. It will thus be seen that these zircons are very much larger than those of either the " Newer " or the " Older " Granite. There can be no doubt that these two types of zircons represent two distinct generations.

Zoisite.—Identified by its extremely low birefringence accompanied by frequent ultra-blues and ultra-browns.

Olivine Gabbro: Dyke in Rhyolites, Wolf Cave.—In the hand specimen this rock closely resembles the gabbro of Ronez. In thin section it is seen to be an olivine gabbro of moderately coarse texture. Large plates of titaniferous augite are wrapped and penetrated in an ophitic manner by a basic plagioclase showing

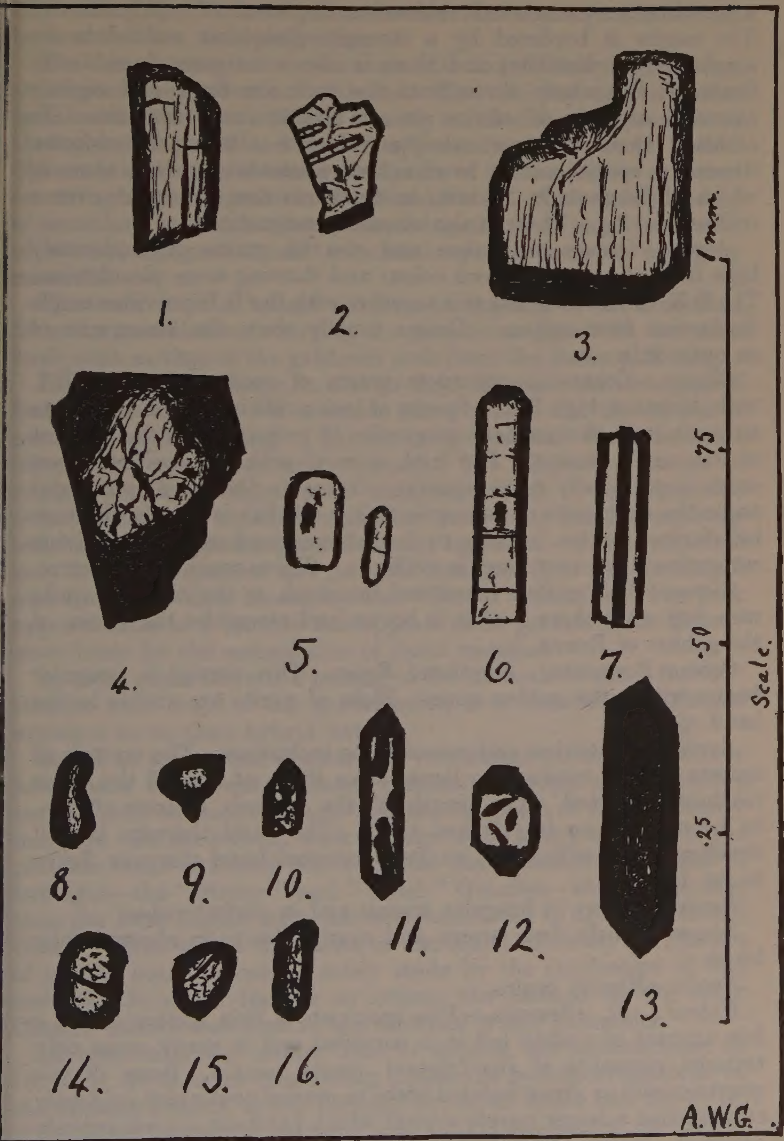

Fig. 1.—Some typical grains drawn to scale. (1 and 3) Clinozoisite, La Moye; (2) Fluor with apatite inclusions, Ronez; (4) Sphene, La Moye; (5) Apatite, Pen Voose, Lizard; (6 and 7) Apatite, La Moye; (8, 9, and 10) Zircons, Gorey; (11) Zircon, La Pulente; (12 and 13) Zircons, La Moye; (14, 15, and 16) Zircons, Pen Voose, Lizard.

a maximum symmetrical extinction angle of 37° (labradorite). The augite is bordered by a strongly pleochroic reddish-brown amphibole (barkevikite) and there is also some green hornblende. Scattered irregularly throughout the rock are large and slightly corroded crystals of olivine in an almost fresh condition. In addition there is some subsidiary biotite altering to chlorite. Accessory apatite occurs as elongated prismatic crystals, some of which although only ·03 mm. in thickness are somewhat over a millimetre long. There is also accessory magnetite.

Augite.—Occurs as broken and cleaved grains of moderately high R.I., of a purple brown colour and showing some pleochroism. The B.R. is moderate and this together with the R.I. provides ample distinction from sphene. Grains usually show the emergence of an optic axis.

Olivine.—Occurs in colourless grains of moderately high R.I. with, however, high B.R. Specks of iron oxide in the mineral cause an increase in the magnetic properties in proportion to the amount of iron oxide present. The fresh mineral with few specks of iron oxide is practically non-magnetic. Owing to the large optic axial angle the emergence of one optic axis is all that is seen in the best interference figures. Owing to the extreme freshness of the olivine serpentine is not very much in evidence. Shows conchoidal fracture.

Zircon.—This residue is unusual inasmuch as the zircon is quite rare, but what there is of it is brown and resembles the zircon of the gabbro of Ronez.

Gabbro Pegmatite : Foreshore, Ronez.—This occurs in irregular bodies within the gabbro mass. Blebs of pyrite are visible in the hand specimen.

Apatite.—Colourless and generally no inclusions. The crystals of apatite in this residue are larger than those of any of the other residues examined. The length of the crystals is from ·5 mm. to 1 mm., and up to ·15 mm. thick. The basal cleavage is well developed and sufficiently so for occasional basal cleavage flakes to be formed.

Pyrite.—Occurs in irregular masses and in perfect cubes.

Zircon.—Fairly deep brown and nearly always in short stubby forms.

Rutile.—Minute grains.

Hybrid : St. Clements.—This specimen in thin section shows a fair amount of quartz but it is corroded and in many cases only tattered remnants of the original quartz remain. Some of the quartz occurs as many isolated blebs in optical continuity evidently representing a larger quartz crystal which has been almost entirely resorbed. Some of the quartz is probably secondary. There are also minute veins of hydatogenetic origin carrying chlorite, epidote, and quartz.

The original felspar has been completely decomposed, being both sericitized and kaolinized, and patches of water-clear secondary albite have been formed. There would thus appear to have been both orthoclase and plagioclase.

The ferromagnesian constituents are hornblende and biotite, accompanied by abundant chlorite. The majority of the biotite is chloritized and in addition there is much chlorite disseminated throughout the rock and not all apparently derived from biotite. Sphene is a common accessory and some of it is secondary as is that occurring in minute grains in chloritized biotite. Quite a fair amount of secondary epidote has been formed together with small quantities of calcite. Magnetite and occasional apatite occur as accessory minerals.

This rock is of a hybrid nature and appears to have resulted from the assimilation or mixing of a granitic magma with one more basic such as that of the gabbroid rock from the Battery, Ronez.

Hybrid: The Hermitage, St. Aubins Bay.—Presents the same general features as the last, but contains more quartz and the felspar is not quite so decomposed. The biotite is fresh and the hornblende idiomorphic and frequently twinned. The plagioclase varies in composition from oligoclase to andesine. Much of its occurrence is in the form of zoned crystals, the inner zone being completely sericitized while the margin is clear and unaltered. Some orthoclase may have been present and perthitic intergrowth is well developed and similar to that shown by the " Newer " Granite. The rock approximates to a tonalite but appears to be granite made slightly more basic by the assimilation of basic material.

In these rocks there is a mixing of the minerals of the " Newer " Granite with those of the gabbro suite, thus furnishing additional evidence as to their hybrid nature.

So far as the author is aware no very definite attempt has ever been made to correlate isolated plutonic outcrops, which possibly may be derived from the same magma, by means of their accessory minerals. In the present work a study of the heavy minerals of the plutonic rocks of Jersey has confirmed the existence of granites of two ages—the " Newer " and " Older " Granites—and for the first time the Fort Regent mass has been associated in age with that of Gorey. Thus within the limits of the island of Jersey correlation of granite outcrops can be safely made by the application of this method. It seems feasible to extend the method to the other Channel Islands and work in this direction is now proceeding.

In conclusion the author has to express his indebtedness to Dr. G. H. Plymen for introducing him to the geological problems of the Channel Islands, to Dr. Plymen, Dr. A. K. Wells, and Mr. S. W. Wooldridge for gifts of material and helpful suggestions, to Dr. A. Brammall and Dr. J. W. Evans for confirmation of certain of the mineral identifications, and to Professor W. W. Watts for laboratory facilities and a critical reading of the manuscript.

The Stratigraphical Horizon and Field-Relations of the Holywell Shales and "Black Limestone" of North Flintshire.

By H. C. Sargent, F.G.S.

Introduction.

In my paper on "The Massive Chert Formation of North Flintshire"[1] certain views were expressed which do not accord with conclusions stated in various Memoirs of the Geological Survey. The object of this paper is to support my views by further evidence.

Briefly, the interpretation of the evidence advanced in this paper is as follows:—

(1) That the Holywell Shales which overlie the Chert Beds on the east of the Chert-outcrop are the homotaxial equivalent of beds between the Carboniferous Limestone *massif* and the Coal Measures in Lancashire, Yorkshire, and the Midlands, and that they should not be referred to the Coal Measures.

(2) That the "Black Limestone" of the Geological Survey on the west of the Chert-outcrop, well developed in the neighbourhood of Prestatyn, is homotaxial with the lower part of the Holywell Shales and younger than the Chert.

Wheelton Hind and J. T. Stobbs also correlated the "Black Limestone" as above defined with the Holywell Shales, and they referred both these formations to Hind's Pendleside Series (1906).[2]

They emphasized the distinction between this "Black Limestone" and the black limestone locally known as "Aberdo", which is developed at various horizons of the Carboniferous Limestone *massif* in Flintshire.

The Holywell Shales.

The definite correlation over wide areas of the beds between the Carboniferous Limestone and the Coal Measures, which has been made possible by Mr. W. S. Bisat's zonal classification of the goniatite fauna, encouraged the belief that a similar succession might be found in the Holywell Shales of North Flintshire. Accordingly, with the valuable co-operation of Mr. E. Montag, a considerable collection of goniatites has been made from the beds on both the west and east of the Chert-outcrop in the north of the county. The specimens were submitted to Mr. Bisat, and he has kindly determined them specifically.

Messrs. R. C. B. Jones and W. Lloyd have also been working in the eastern district recently, and they have obtained valuable additional results, which they kindly allow me to record. The combined result has fully justified the anticipation.

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[1] Geol. Mag., Vol. LX, 1923, pp. 168–83.

[2] Dates in brackets refer to "References" at the end of the paper.

The table below indicates the zones so far established, the localities where the specimens were collected, and the strata represented by the zones in other areas. It will be observed that the zonal sequence shown by the table corresponds with the sequence in Lancashire, Yorkshire, and elsewhere, and is in short quite normal.

ZONAL SUCCESSION IN THE HOLYWELL SHALES OF NORTH FLINTSHIRE.
(Mr. W. S. Bisat's classification.)

		ZONE.	LOCALITY.	ZONAL STRATA.
UPPER CARBONIFEROUS (Lancastrian).	G *Gastrioceras.*	*Cancellatum.*	Panton Hall Valley (S.E. of Holywell). Talargoch Mine, Meliden (tip-heap, Mostyn Shaft).	Shales below the Rough Rock.
	R *Reticuloceras.*	*Reticulatum,* mut. *β.* *Reticulatum,* mut. *α.*	Coed Pen-y-maes (near Holywell).	Shales associated with the "Middle Grits" of Lancs. and Yorks.
		Reticulatum (type). *Inconstans.*	Coed Pen-y-maes (near Holywell). Walwen Valley (lane near Cefn Cottage).	Sabden Shales.
	H *Homoceras.*	*Proteum* cf. *Diadema.*	Glyn Abbott Road, Holywell.	
	E *Eumorphoceras.*	Cf. *Bisulcatum.*	"Holywell Shales, Holywell."	
		Cf. *Pseudobilinque.*	Walwen Valley (lower part, below "Sheepfold").	Bowland Shales (upper part).
LOWER CARBONIFEROUS (Viséan).	P *Goniatites* (s. str.).	No determinable Lower Carboniferous Goniatites have so far been obtained from the Holywell Shales, but the occurrence of *Posidonomya becheri* (Bronn), as stated in the text, indicates that the lowest beds are of P age.		Bowland Shales (lower part).
		CHERT-BEDS.		
		CARBONIFEROUS LIMESTONE.		

Note.—The zones of *Reticulatum* (type) and muts. *α* and *β* were proved by Messrs. R. C. B. Jones and W. Lloyd. The specimen of *Bisulcatum* was from the collection of the late Mr. J. H. Grundy, now in the possession of Mr. E. Montag. Mr. J. W. Jackson has recorded the zone of *Proteum* and *Diadema* ("Sabden Shale Fossils near Holywell, Flintshire," *The Naturalist*, June, 1925).

A glance at the table will show that all the Upper Carboniferous zones included therein are older than the Coal Measures. The highest zone, *Cancellatum*, is at the summit of the Holywell Shales, as defined by the Survey (1923, p. 36), and is on the horizon of the shales below the Rough Rock, which is at the top of the Millstone Grit series in other areas.

Mr. C. B. Wedd, contesting Hind and Stubbs' views, noted above, and supporting the conclusion that the Holywell Shales should be referred to the Coal Measures, states, *inter alia*, that the goniatite genus *Gastrioceras* "ranges upward from approximately the base of the Holywell Shales" (1923, p. 25). The only record I have been able to find of its occurrence below the horizon shown in the table is the following :—" . . . in the tip-heaps of two old lead-shafts, which passed through a few feet of the basal shales before entering the Chert just below the quarry by the side of the vein-bearing fault 220 yards north-west of Kelston Farm, *Gastrioceras* was found in the Shale" (1923, p. 33).

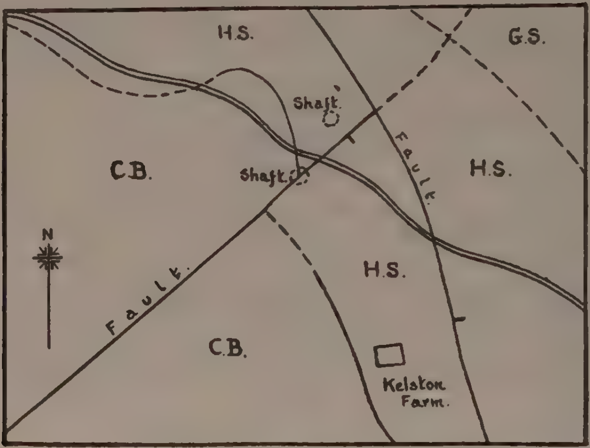

Fig. 1.—Area near Kelston Farm, North Flintshire. (Reproduced from 6 in. Quarter Sheet, Flint, II, S.W.) Scale: 6 in. = 1 mile. G.S. = Gwespyr Sandstone. H.S. = Holywell Shales. C.B. = Chert Beds.

These tip-heaps have been carefully searched and obscure goniatites found thereon were submitted to Mr. Bisat. His report was as follow :—" The specimens from near Kelston Farm are too fragmentary for anyone to attempt a specific determination. I do not think they can be *Gastrioceras*, as there is no sign of umbilical tubercles. They may be *Inconstans* again, but it is almost impossible to say."

Dr. Neaverson has also collected obscure goniatites on these tip-heaps. He considers they probably include *R. inconstans* and possibly higher forms.

The sketch-map (Fig. 1) shows the position of the two mine-heaps in regard to the faults that have disturbed the beds of the locality. The material of the southern tip-heap consists of Chert and Holywell Shales; that of the northern tip-heap of Holywell Shales and Gwespyr Sandstone.

The normal succession of these beds is:—

3. Gwespyr Sandstone.
2. Holywell Shales.
1. Chert Beds.

The Gwespyr Sandstone is separated from the Chert Beds, on the basis of the Abbey Mills boring, by 420 feet[1] of Holywell Shales (1923, p. 30). It is obvious, therefore, that a long vertical range of rocks is represented by the material on the tip-heaps, and the fossils also indicate that widely separated zones are present. The Holywell Shales have been faulted down against the Chert Beds, and it seems inconceivable that any given piece of shale lying on the tip-heaps can be determined as derived from the "basal shales" or any other definite horizon relative to the Chert Beds. Much better evidence seems to be required before that of the material collected in situ is rejected.

All the goniatites so far determined from the Holywell Shales on the east of the Chert-outcrop are Upper Carboniferous forms, but the presence of Lower Carboniferous beds of P age, directly overlying the Chert Beds and correlative with the lower part of the Bowland Shales, is clearly indicated by the occurrence of *Posidonomya becheri* (Bronn). It is, moreover, obvious on the ground that a great thickness of Holywell Shales must intervene between the top of the Chert and the locality where the lowest zone of the Upper Carboniferous (*Pseudobilingue*) is indicated. The ground is smothered in Drift and exposures are scarce. From these beds in Grange Quarry, near Holywell, Hind and Stobbs record *Posidonomya membranacea* (McCoy) "abundant" (1906, p. 451). From the same shales overlying the Chert at the Pentre Quarries, near Gronant, they record *P. becheri* "rare" (ibid.), and again, "rather rare" on the roadside between Holywell and Brynford (ibid., p. 453). Hind regarded both these fossils as "absolutely characteristic of this horizon, having never been found in higher beds" (ibid. p. 504). It is now recognized, however, that while *P. becheri* is a strictly Lower Carboniferous form and does not range above zone P, *P. membranacea* persists up into zone E of the Upper Carboniferous.

Further collections of *P. becheri* have recently been made by Jones and Lloyd from siliceous shales overlying the Chert in an old quarry 400 yards north-west of Holywell Workhouse. Strahan records "*Posidonomya*" from the same quarry (1890, p. 50).

Corroborative evidence has also been obtained by Montag, who has recently collected the same fossil from the neighbourhood of the Talacre Mine, near Gronant. The shale containing the specimens was lying in the cart-track at the entrance to the precincts of the mine; at some little distance from the tip-heaps. Although not in situ, there cannot be much, if any, doubt that it came from the near neighbourhood.

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[1] Hind and Stobbs estimated the thickness at about 1,000 feet on the evidence of the Bagillt-Halkyn water-level (1906, p. 456). The Abbey Mills boring showed a fault at the base of the Holywell Shales, and this may conceivably have cut out some of the lower beds. But see *Liverpool Memoir*, 1923, p. 27.

There thus appears to be sufficient evidence to establish the Lower Carboniferous (P) age of the lowest beds of the Holywell Shales.

Fossils are scarce in these basal shales on the east of the Chert-outcrop. The explanation is probably to be found in their extremely siliceous character, as shown by Strahan (1890, p. 65) and the present writer (op. cit., p. 174). Hind and Stobbs' records from this part of the area are very scanty. The abundant silica in the beds is of a crypto-crystalline character and it seems clear that the deposition of the limestone and shales comprising the Holywell Shales had begun before the complete termination of the Chert episode.

All the localities shown in the table from which goniatites have been obtained in the Holywell Shales are on the east of the Chert-outcrop, except the tip-heap of the Talargoch Mine at Meliden, which is in the Vale of Clwyd on the west. Here the beds are brought down by the Prestatyn fault, and they are concealed from view by a great thickness of Drift. The goniatites collected on the tip-heap establish the presence of the *Cancellatum* zone, the highest zone of the Holywell Shales, occurring also in the Panton Hall Valley on the east. Careful search revealed no other forms, but it is clear from the description in the Survey Memoir (1885, p. 21) that a great thickness of the Holywell Shales is present. The lower beds have been cut out by a fault running approximately E. to W. (ibid. and map in Memoir).

The throw of this fault must be of considerable magnitude since it has brought down the *Cancellatum* beds (G) against "Black Limestone", which, as will be shown below, is of P age. Since, therefore, the highest and lowest zones are present, the conclusion seems justifiable that the beds faulted down in the mine represent zones intermediate between G and P, and that the Holywell Shales on the west of the Chert, in the neighbourhood of Prestatyn, are correlative with those on the east in the neighbourhood of Holywell. (Fig. 4.)

The true position of the Holywell Shales in the geological column appears now to be clear. The lowest beds are referable to zone P of the Lower Carboniferous and the remainder represent the Millstone Grit Series of other areas, Lancastrian of Bisat.

THE "BLACK LIMESTONE".

The formation discussed in this section consists of black, argillaceous limestone with interbedded shales. It is well developed in the neighbourhood of Prestatyn, and is stated in the 1885 Survey Memoir (p. 18) to underlie the Chert Beds.

This formation is clearly differentiated, both faunistically and lithologically, from the Carboniferous Limestone of the *massif*. "The thin regular bedding, the sharply cut joints, dark colour and conchoidal fracture of these beds render them distinguishable at a glance from the ordinary type of limestone". (1885, p. 16.)

Diligent search has been made for fossils in these beds. *Posidonomya becheri* is common in the shales, as noted also by Strahan (1885, p. 17). *Pterinopecten* "*papyraceus*" occurs frequently. Obscure and crushed goniatites have also been found, but unfortunately none of them has proved capable of definite determination.[1] Mr. J. W. Jackson has been more fortunate, and he kindly allows me to state that he has found *Goniatites sphaerico-striatus* (Bisat), a fossil characteristic of the horizon of the Lower Bowland Shales (P) in the quarry at Teilia.

It is obvious, therefore, that these beds are of P age, and it seems clear that their correlation by Hind and Stobbs with the lower part of the Holywell Shales on the east of the Chert-outcrop was justified.

A comparison of the lithological characters supports the same correlation. Precisely the same type of thin-bedded, platy, black limestones, with interbedded shales, characterizes the two formations. Under the microscope the limestones from both areas are seen to have the same fine-grained laminated character. Megascopically they are indistinguishable the one from the other. The black limestone of the *massif*, though sometimes fine-grained, is generally much coarser in texture, and does not show the same fine-bedding under the microscope.

It is true that the basal beds of the shales on the east are more siliceous than those of the western area, a feature probably due to local conditions, as noted above. Moreover, in the eastern area the shaly facies predominates over the limestone, whereas the reverse is the case in the west. Greater proximity to a coastline on the east may explain this difference. Essentially, and as a whole, there is a remarkable lithological resemblance between the two formations.

The stratigraphical relations between the "Black Limestone" and the Chert Beds are, owing to the disturbed character of the area and the absence of exposed junctions, very difficult to elucidate, and probably they can only be definitely established by considerable excavation. There are, however, definite and strongly marked surface features, which appear to indicate a faulted junction between the two formations, The sketch-map (Fig. 2) shows the interpretation I venture to make of these features.

The steep hillside east of Top Nant Farm consists of Chert, and forms a conspicuous feature. A large exposure of the rock is entirely brecciated, strongly suggesting disturbance (cf. 1906, p. 503).

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[1] Mr. Bisat reports that they probably represent some part of the Bowland Shales.

West of this feature " Black Limestone " occupies the valley at the foot of the hill. The limestone has been disturbed and has apparently been brought down against the Chert by a fault which may be named the Top Nant Fault. South of the farm the surface is covered with Drift, but a shallow, eroded channel trending south-south-east, with water oozing up from below, is suggestive of a continuation of the fault in that direction. The massive Chert formation ends abruptly against this line of fault, and is seen no more on its western side except in attenuated form, as noted below, in the Nant-y-mwyn shaft, and possibly at Meliden, a mile to the south, as part of the down-faulted area west of the Prestatyn fault. (Fig. 4.)

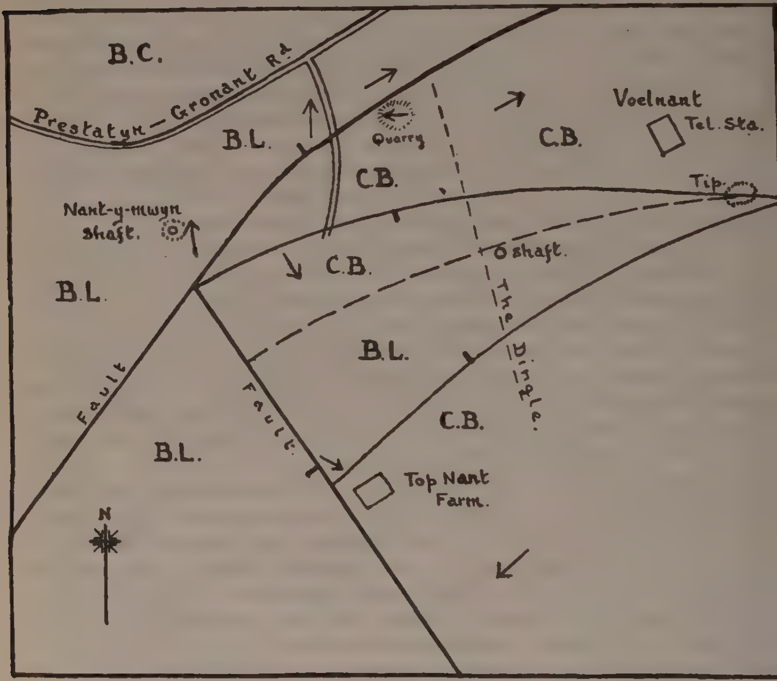


Fig. 2.—Sketch-map of area north of Top Nant Farm, near Prestatyn. Scale: 6 in. = 1 mile. B.C. = Boulder Clay. B.L. = " Black Limestone." C.B. = Chert Beds.

The fault in the neighbourhood of Nant-y-mwyn, having a general N.E. to S.W. direction, corresponds approximately with Strahan's " sharp faulted anticlinal, the axis of which runs towards Nant-y-mwyn " (1885, p. 16). This fault is marked in part of its course by a strong feature on the hillside north of Top Nant Farm.

The ground slopes down northward. The feature consists of a steep bank of Chert and Cherty Shales running along the higher (south-eastern) side of the line of fault. Below this feature the beds, sloping down northward, consist of " Black Limestone ". They are exposed in an old quarry at Nant-y-mwyn, in the lane on the east, and again further east where a dip is shown on the map. The feature and the varying dips in the two formations make it difficult to doubt the existence of a fault bringing down the " Black Limestone " against the Chert Beds.

The presence of " Black Limestone " in the Drift-covered, down-faulted area north of this fault and of the road was proved by Mr. Montag and myself in the summer of 1922, when we were enabled to enter an old adit-level which had been driven south through the Drift into the hillside. The walls, roof, and floor of the level, which was nearly 6 feet high, were constructed of brick until the rock was reached. This proved to be " Black Limestone ", dipping north.

An interesting petrographic feature in a thin section of this rock in the level is the presence of numerous rhombs of dolomite. No other occurrence of this feature has been noted in the beds discussed in this paper, except in the highest beds of the Chert and the overlying Holywell Shales at Gronant, less than a mile away (H. C. S., op. cit., p. 176). A further resemblance is the siliceous character of parts of the rock, similar to the " bastard Chert " at Gronant (ibid., p. 174). It seems possible that the two beds are on the same horizon, overlying the Chert Beds.

The structure appears to be complicated by two smaller faults bringing down a wedge-shaped block of Chert and " Black Limestone " north of Top Nant Farm. The throw of the northern one is probably very slight. It includes in its course the " joint ranging nearly east and west " near the Voelnant Telegraph Station (1885, p. 50).

The Chert within the block dips into the hill towards the farm, but the boundary between it and the " Black Limestone " is uncertain, and it is therefore indicated by a broken line on the map. Eastward, on the side of a steep ravine known as " The Dingle ", which may perhaps mark another line of fracture, " Black Limestone " is seen at the surface in an old mine-shaft. Again, further east, near the Voelnant Telegraph Station, " Black Limestone " and Chert are associated on an old mine-heap close to the joint above-mentioned.

West of the Top Nant Fault, which marks the abrupt eastern boundary of the Chert Beds, as noted above, there are many exposures of " Black Limestone ", but nowhere, either in the valleys or on the hills, can Chert be seen resting upon it. Considering the highly resistant nature of the rock, this is thought to be strong presumptive evidence against the view that the Chert Beds are younger than the " Black Limestone ".

On the other hand, it must be admitted that nowhere in the district can Chert be seen *underlying* the "Black Limestone", with one possible exception. "On the west side of the Prestatyn fault the Black Limestone outcrop is shifted to the south of Meliden, a distance of about a mile and a quarter" (1885, p. 16). In an old quarry in this down-faulted area, about 290 yards south-east of Meliden Station, the following succession is seen :—

3. "Black Limestone."
2. Chert.
1. Carboniferous Limestone.

The Chert (No. 2) is a band about 6 inches thick, and it is suggested that it is probably the attenuated western margin of the massive Chert Beds of North Flintshire. The Chert *within* the Carboniferous Limestone of this immediate area occurs in thin strings and small nodules, so that the occurrence marks at any rate a stronger cherty phase at the close of the Carboniferous Limestone episode, even if the rock does not form part of the main Chert Beds.

In the grounds of Terfyn, about a mile east of Prestatyn, "an old quarry shows chert resting on dark limestone" (1885, p. 16). This is the only exposure of the undoubted base of the Chert Beds in the Prestatyn area. On the east of the outcrop, from Trelogan south for 6 or 7 miles, Chert is seen in several localities resting directly on the Carboniferous Limestone.

Field and microscopic examination of the "dark limestone" of the Terfyn Quarry leave little doubt that here too the same relations exist between the two formations. The "dark limestone" is of Carboniferous Limestone ("Aberdo") type. Palaeontological evidence is wanting, but it lacks the thin-bedded platy character of the "Black Limestone". Under the microscope it is seen to be in part much coarser grained than the latter, in part fine-grained resembling some specimens of "Aberdo", but without the fine lamination characteristic of the "Black Limestone".

There appears thus to be strong evidence that in the Prestatyn area the Chert Beds rest directly on the Carboniferous Limestone, as is the case in the east.

The thickness of the "Black Limestone" in the Prestatyn area "probably rather exceeds 200 feet" (1885, p. 18). The succession in this area according to the Survey Memoir is as follows :—

3. Chert Beds.
2. "Black Limestone" (P beds).
1. Carboniferous Limestone (D beds).

On the east of the outcrop the succession is :—

3. Holywell Shales (lowest beds of P age).
2. Chert Beds.
1. Carboniferous Limestone (D beds).

To explain this extraordinary inversion in the succession it would seem necessary to assume that the Chert Beds have shifted their horizon by 200 feet within a distance of less than a mile from

Gronant on the east to Top Nant Farm on the west, or within less than half a mile westward of the Terfyn Quarry above-mentioned. Field evidence lends no support to such an assumption.

The tip-heap of the old Nant-y-mwyn shaft (Fig. 2) affords further presumptive evidence. The material on the tip-heap shows a rough stratification, obviously in the reverse order of that of the beds when in situ. After the Drift from the surface (the lowest bed in the tip-heap), the next bed is " Black Limestone " ; then follows Chert, with Carboniferous Limestone above.

The foregoing evidence seems to support strongly the conclusion that the " Black Limestone " of P age, on the west of the Chert-outcrop, is younger than the Chert, and that it is on the same horizon as the lower beds of the Holywell Shales on the east.

The Transgressions.

In my former paper (op. cit. p. 172) an attempt was made to show that the " Black Limestone " transgresses the Chert Beds in the Prestatyn area on the west, where it comes to rest directly on the Carboniferous Limestone. The evidence may be briefly re-stated and amplified.

It is known that the Chert Beds thin out rapidly westward. They were not met with in the workings of the Talargoch Mine at Meliden, in the Vale of Clwyd, where, according to the Survey Memoir (1885, p. 21), they are cut out by the fault referred to above, bringing down Holywell Shales against " Black Limestone ". " It is probable that the Chert beds were much thinner here than near Gronant, for in other parts of the Vale of Clywd *they are known to have thinned out completely*." (Ibid. The italics are mine.)

The only evidence that the beds were ever present in this locality is the statement that " fragments of the rock occur abundantly in the veins at the north-east end " (ibid.). There is no evidence as to the horizon, whether above or below the " Black Limestone ", from which these fragments were derived. It is clear from the map in the Memoir that the " Black Limestone " here is within the area that was shifted a mile and a quarter to the south, as noted above. It is significant that the Chert occurred only in the north-east—the point nearest to the main Chert Beds, although shifted a long distance by the Prestatyn fault.

It seems probable, therefore, that the fragments represented the attenuated western margin of the Chert Beds which had completely thinned out further west. It is possible that they were derived from the same bed below the " Black Limestone " as that in the old quarry at Meliden, noted above, distant about a quarter of a mile to the south.

On the steep hillside above Fforddlas (Prestatyn) ; in the Teilia Quarry ; and at other localities, all at a considerable distance *west* of the Chert-outcrop, the " Black Limestone " is seen resting directly on the Carboniferous Limestone, though without any appearance of unconformity.

If the view, suggested by the evidence brought forward in this paper, that the "Black Limestone" is the equivalent of the lower part of the Holywell Shales, and therefore younger than the Chert, is correct, the evidence of the transgression seems to be clear and convincing.

Strahan shows that a similar transgression occurs on the south of the Chert-outcrop. In the neighbourhood of Rhyd-y-mwyn the Chert Beds have thinned out completely and Holywell Shales pass directly on to the Carboniferous Limestone. "The overlap, though rapid, is unaccompanied by any appearance of unconformity". (1890, p. 53.)

Fig 3

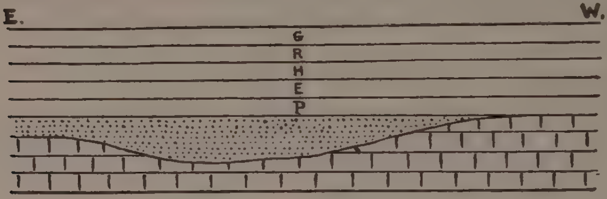
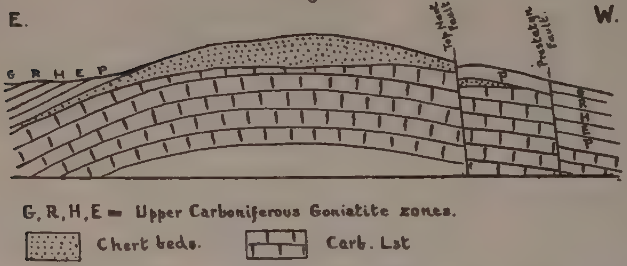


Fig 4



Figs. 3 and 4.—Diagrams illustrating the stratigraphy of the Carboniferous rocks below the Coal Measures in the north of Flintshire. Not drawn to scale. Fig. 3. The beds as deposited. Fig. 4. After elevation and erosion.

These rapid transgressions support the view expressed in my 1923 paper that the Chert Beds were deposited in a basin in the Carboniferous Limestone.

The diagrams (Figs. 3 and 4) illustrate my conception of the stratigraphy of the area discussed in this paper. As already mentioned, it is probable that these vexed questions can only be definitely settled by considerable excavations. By their result, if ever undertaken, the views set forth above must stand or fall.

ACKNOWLEDGMENTS.

I have to acknowledge with grateful thanks my indebtedness to many friends:—To Mr. E. Montag for unwearied assistance in the field and for valuable criticism; to Mr. W. S. Bisat for the pains he has taken in the determination of goniatites; to Professor Boswell and Dr. Neaverson (without implying their agreement with my views) for valuable assistance in the field; and to Messrs. R. C. B. Jones and W. Lloyd for their additions to the faunal list. Dr. L. R. Cox and Mr. C. P. Chatwin have also kindly lent their assistance to the determination of lamellibranchs.

REFERENCES.

1885. *The Geology of the Coasts adjoining Rhyl, Abergele, and Colwyn*, by A. Strahan. Mem. Geol. Surv.

1890. *The Geology of the Neighbourhoods of Flint, Mold, and Ruthin*, by A. Strahan. Mem. Geol. Surv.

1906. "The Carboniferous Succession below the Coal Measures in North Shropshire, Denbighshire, and Flintshire", by Wheelton Hind and John T. Stubbs: GEOL. MAG., Dec. V, Vol. III, pp. 385–400, 445–59, 496–507.

1923. *The Geology of Liverpool, etc.*, by C. B. Wedd, B. Smith, etc. Mem. Geol. Surv.

Some Problems of Physical Geology and the Earth's Thermal History.

By ARTHUR HOLMES, D.Sc., A.R.C.S., F.G.S., The University, Durham.

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1. INTRODUCTION.

IN a recent paper [1] I stated that the hypothesis of a continuously cooling earth had "consistently failed to lead to any adequate explanations of fissure eruptions and other volcanic and tension phenomena, mountain-building processes and their distribution in time and space, and the alternation of marine transgressions and recessions". It seems to be desirable that I should further justify this sweeping integration of objections, for Dr. Harold Jeffreys, who has actively explored the consequences of this theory during recent years,[2] takes exception to my discouraging view of the

[1] GEOL. MAG., July, 1926, pp. 306–7.

[2] *The Earth*, Cambridge, 1924.

position, and claims that the alleged failures include the principal successes of the theory.[1] The evidence on which my summary indictment was based will be reviewed in this paper; and attention will be directed to certain other phenomena—such as the growth of geosynclines—of which the significance has not yet been generally realized. As a preliminary it will be convenient to discuss the gradually converging evidence bearing on the thickness and substructure of the continents.

2. The Thickness of the Continents.

It has been pointed out in previous papers[2] that "a maximum estimate of the mean thickness of the average rocks (*sial*) of the continents can be arrived at by equating the amount of heat escaping at the surface with the heat generated within the *sial*". The heat lost per year from a column of the crust of unit cross section averages about 63 calories. This could be entirely supplied by the disintegration of the uranium, thorium and potassium in 15 km. of average granite or in 20 km. of average igneous continental rock. If it be supposed that the abundance of the radioactive elements falls off rapidly in depth, then even more than 20 km. might be necessary. There is evidence of such a downward decrease in radioactivity in the composition of the granitic rocks that invaded the crust in Pre-Cambrian times. The original rocks appear to have been of granodioritic composition and the action of magmatic processes appears to have enriched the upper levels in granite at the expense of the lower levels, which, on this hypothesis, must have approached more and more closely to diorite.[3] A downward passage of granite into diorite implies a downward decrease both in potassium and in the more energetic radioactive elements; but even allowing fully for this the *sial* cannot much exceed 20 km. in average thickness, for in addition to the heat generated within it, heat must also ascend from the still hotter rocks of basaltic and peridotitic composition that lie beneath.

The above argument depends for its validity on the assumption that the energy released by the radioactive elements is all converted into heat. In his second Presidential Address to the Geological Society, Dr. J. W. Evans adversely criticizes this assumption.[4] He says, "it is probable that a considerable proportion of the energy liberated by such elements, when they occur as rock constituents, is used up in effecting physical, chemical, or atomic changes in the surrounding minerals." Now if this view were correct we should expect the heat developed by radium in a glass container, and determined experimentally, to be much less than the heat equivalent calculated from the numbers and energies of the rays emitted. Yet, despite the fact that the glass container rapidly becomes intensely coloured by such processes as Dr. Evans has in mind, the calculated and determined values of the heat generated agree surprisingly closely. The total heat developed by one gram of radium with its short-lived products was found by St. Meyer and Hess to be 137 calories per hour. The calculated heat equivalent of the energy emitted as α-, β-, and γ- rays is 137·14 calories per hour. We may therefore conclude with Lord Rayleigh[1] and Dr. R. W. Lawson[2] that the evidence decides conclusively against Dr. Evans' view. The ceaseless outpouring of energy that is taking place in the rocks beneath our feet is practically all converted into heat, and the thermal method of determining the limiting thickness of the continents is therefore valid.

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[1] Geol. Mag., Nov., 1926, p. 517.

[2] Geol. Mag., July, 1926, p. 311. A. Homes and R. W. Lawson, *Phil. Mag.*, Dec., 1926, p. 1227.

[3] Geol. Mag., July, 1926, pp. 317–18.

[4] *Q.J.G.S.*, lxxxii, 1926, p. lx.

In the same Address, Dr. Evans calculates the thickness of the *sial* of plains (here called the average thickness of the continents) to be a little over 40 km. This result is definitely at variance with the thermal implications of the radioactivity of the rocks. The underlying assumption on which the calculation is based is that the deepest folds of mountain regions go down to the depth of 86 km. below sea-level. The assumption is merely an interpretation of the meaning of the depth of isostatic compensation as determined by the methods—chosen for their mathematical convenience—of Hayford and Bowie. A more plausible interpretation is discussed by Jeffreys in a recent paper on isostasy[3] according to which the depth of the deepest folds would be roughly half that assumed by Dr. Evans. Corresponding to this conclusion, it is interesting to notice that, if we reverse Dr. Evans' problem and assume the thickness of the *sial* of the plains to be 20 km., the maximum depth of folds for mountains standing 5 km. above sea-level works out at a little over 40 km.

Another recent estimate of the thickness of the continents which ignores the implications of radioactivity is that adopted by Daly in his book *Our Mobile Earth*, 1926, p. 122. He quotes Gutenberg as his authority for the assumption of a "granitic layer" 55 km. in thickness. Such a thickness would involve permanent fusion towards the base, and much lower seismic wave velocities than are observed.

Fortunately there is quite independent seismic evidence supporting a far more limited average thickness. From surface waves of known period that had traversed the continental crust Gutenberg calculated the average thickness to be about 30 km. A more rigorous discussion of the data by Jeffreys, taking dispersion into consideration, pointed to a thickness of 15 km.[1] If the granite of the continents passes down into diorite this result would be too low, and that it probably is too low is made clear by the latest work of Jeffreys on the interpretation of seismograms.[2] Quite recently he has found that compressional waves are transmitted through a superficial layer 10–15 km. in thickness with a velocity of 5·6 km. per second. This agrees exactly with the velocity in granite as calculated from the density and compressibility of granite at pressures corresponding to the depths involved. Next there is an intermediate layer (not sharply differentiated) of the same order of thickness in which the velocity is about 6·2 km. per second. This satisfies the data for either basaltic glass or diorite. Of these alternatives I have tried to show that diorite is by far the more probable.[3] Still deeper the velocity rises to 7·8 km. per second. The available work on the compressibility of rocks at high pressures—carried out by L. H. Adams and his colleagues at the Carnegie Institution of Washington—suggests dunite as a possible material at such depths. The corresponding calculated velocity is then, however, 8·2 km. per second, which is too high, and I have suggested that a preferable interpretation would be eclogite passing down into dunite at some depth at present unknown. It is hoped that this tentative hypothesis will soon be put to the test by an experimental determination of the elastic properties of eclogite at high pressures.

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[1] *The Observatory*, Feb., 1926, p. 57.

[2] *Phil. Mag.*, Dec., 1926, p. 1226. *Nature*, 19th Feb., 1927, and 14th May, 1927.

[3] *Gerlands Beiträge zur Geophysik*, Bd. xv (2), 1926, p. 167.

Meanwhile the deduction can scarcely be avoided that material of basaltic composition does lie beneath the lighter rocks of the continents. But if the latter consist of granite and diorite to a thickness ranging between 20 and 30 km., then the "basaltic layer" cannot exist in the state of glass as Daly supposes[4]; nor is any appreciable thickness of gabbro likely to be present, since the velocity of the corresponding compressional waves would then be 6·8 or 6·9 instead of 7·8 km. per second. Some other facies of basaltic material thus seems to be implied, and this may well be eclogite, in which the velocity to be expected should not be very different from that in dunite. Calculations based on the molecular volumes of the minerals of eclogite indicate a velocity lying between limits of 7·6 and 8·1 km. per second.

The least uncertain of Jeffreys' determinations of the depths of the upper layers is that based on the Tauern earthquake of 1923. The uncorrected results, which are probably too high, indicate 12 km. for the granite layer and 25 km. for the underlying layer. Apart from systematic errors that are at present difficult to evaluate, a high result would here be expected because the records examined were those of waves propagated through the rocks beneath high mountains. An estimate of 37 km. for the thickness of the *sial* in this part of Europe is therefore not inconsistent with an estimate of some 20 km. for regions of average elevation.

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[1] *M. N. Roy. Ast. Soc. Geophys. Suppl.*, vol. i, No. 6, 1925, p. 282.

[2] *Nature*, 25th Sept., 1926, p. 443. Geol. Mag., Nov., 1926, p. 523. *M. N. Roy. Ast. Soc. Geophys. Suppl.*, vol. i, No. 8, 1926, p. 385.

[3] *Nature*, 23rd Oct., 1926, p. 586.

[4] *Our Mobile Earth*, 1926, p. 100.

So far our estimates of average continental thickness are of the order 15 to 30 km. A lower limit is provided by the thickness of sediments and volcanic rocks accumulated in geosynclines. The deepest geosyncline of the past for which data are known is that now represented by the Cordillera of North America. In the area of greatest subsidence, from Idaho to British Columbia, 30,000 feet of Proterozoic formations were succeeded by 26,000 feet of Palaeozoic and 20,000 feet of Mesozoic formations before the orogenesis of the Late Cretaceous brought the geosyncline to the end of its amazingly long history.[1] It is not certain that these estimates of thickness can be interpreted to mean that the original floor of the geosyncline subsided some 22 km. in all, though Schuchert, who has made a special study of this geosyncline definitely makes such an interpretation. Owing to lateral growth of sediments and consequent overlapping, the total thickness of the accumulation of sediments may be greater than their original vertical depth. Schuchert, however, is well aware of the ambiguous character of the term *thickness*, and as he clearly uses it in the sense of *vertical depth* we may provisionally assume that the subsidence of the great Cordilleran geosyncline approached a maximum of about 20 km.

The deepest formations in this long sequence are altered by load metamorphism, the density being raised in consequence to just over 2·7.[2] Some of the volcanic beds have also a density exceeding 2·7, but against this the younger sediments have lower densities, and before the Laramide orogenesis and the associated igneous activity their densities would be still lower. The average density of the completed sequence of formations before orogenesis must certainly have been less than 2·7. It follows from this that the borderlands of the geosyncline, when worn down to nearly sea-level, must have been underlain by more than 20 km. of *sial* having an average density of 2·7. It is a direct deduction from the principle of isostasy that the average thickness of the continents must be greater than the greatest depth of sediments accumulated in a geosyncline, provided that the latter began in a region that was previously above sea-level. So far as the evidence goes this suggests that the average thickness of the continents is at least of the order 20 km.

Summing up, we have reached certain tentative conclusions, giving for the average thickness of the *sial* of the continents the following provisional estimates :—

(*a*) from the thermal argument :
not more than 20 *km.* (+)[3]

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[1] C. Schuchert, *Bull. Geol. Soc. Am.*, xxxiv, 1923, p. 191.

[2] R. A. Daly, *Geol. Surv. Canada*, Mem. 38, 1921, p. 173.

[3] The plus and minus signs indicate the direction of possible corrections.

(*b*) from the evidence of surface waves:
more than 15 *km.* (+)
(*c*) from the evidence of compressional waves:
between 20 *and* 30 *km.* (—)
(*d*) from the depth of subsidence of the deepest geosyncline:
more than 20 *km.* (—).

Though none of these estimates could at present be regarded as final if standing alone, they are all independent, and together they converge towards a figure of 20 km. which is evidently of the right order to satisfy all the date available.

3. THE GROWTH OF GEOSYNCLINES:

In the paper referred to in the *Introduction*, Jeffreys pleads that the hypothesis of a continuously cooling earth cannot be said to have failed to account for marine transgressions and recessions since it has not tried. The failure to suggest an adequate explanation still remains however, and it may be reasonably attributed to the fact that the hypothesis provides no appropriate opportunities for fusion in the depths; for relative lateral movements of crust and underlying magma; or for widespread stretching of the materials in the zone of flowage. The difficulties that arise appear in their most acute form as soon as an attempt is made to explain geosynclines.

Let us consider the possible processes that can start an extensive land or other area on a long-continued course of depression. From the point of view of isostasy it is a necessary condition that approximate balance should be maintained between the depressed area and its borderlands. The amount of mass beneath the subsiding region remains substantially the same throughout, and therefore the controlling condition for a downward flexure of the surface is an effective decrease in volume of the underlying material. This may be achived:—

(*a*) by greater thermal contraction beneath the sinking area than takes place beneath the adjoining regions;

(*b*) by a similar differential contraction due to change of state or phase, e.g. by consolidation of magma, or transformation of a low-pressure facies of rocks into a high-pressure facies; or

(*c*) by a redistribution of material in depth involving the flowing out of the lighter material of the original floor of *sial*, accompanied by the inflow of an equal mass of heavier material.

On the hypothesis under discussion the utmost that can be ascribed to differential thermal contraction is an uncompensated sagging of the ocean floor near its boundary with a continental mass, amounting in all to about 1 kilometre of additional depth.[1] The result is in the right direction, but is inadequate, as some of the actual oceanic deeps go down 4 or 5 kilometres further than the average ocean floor. Some very different process seems inevitably to be concerned in the origin of these mysterious features. Fissures filled from below by peridotite might satisfy the conditions, but this is an interpretation totally different from anything that is taken into consideration by the hypothesis of continuous cooling.

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[1] H. Jeffreys, *The Earth*, 1924, p. 140.

Nevertheless the hypothesis does provide a downward sag up to about 1 km., thus increasing the depth of the ocean along the continental margins to over 5 km. in places. If the resulting depressed belts were subjected to long-maintained sedimentation, then, owing to the further depression caused by the loading of the region from above, the maximum thickness of the sediments which could accumulate would be of the order 10–20 km. This follows from the general formula $S = w\ (D-1)/(D-d)$, where S is the maximum thickness of material of average density d which can accumulate in a basin having an original depth of water w of density 1. D is the density of the material displaced in depth. Taking $w = 5$ km.; $D = 3{\cdot}4$; and $d = 2{\cdot}4$; we find $S = 12$ km. If D be taken as 3·2, then S becomes 14 km.; and if in addition d is taken as 2·6, to allow for load metamorphism, then S rises to 18 km.

These results would meet the requirements of most of the geosynclinal accumulations of strata but for one fatal defect in the initial conditions. In all the well-known examples the geosynclines were originally land areas or shallow seas, not oceanic deeps.

Let us next consider a land area at sea-level which develops into a geosyncline. We shall begin with a vertical column made up of an upper layer of *sial* of average density 2·7, resting on an underlying layer of material having in its upper parts a density of 3·4. Suppose at a later stage, the region having subsided, the surface is again at sea-level owing to the accumulation of a thickness h of sediments of average density 2·4. If the thickness of the material displaced in depth be x, then by the principle of isostasy we have $2{\cdot}4\ h = 3{\cdot}4\ x$; giving $x = 2{\cdot}4\ h/3{\cdot}4$. The lower boundary of the original *sial* is depressed by an amount x, while the upper boundary (the initial floor of the geosyncline) is depressed by an amount h. Thus the original *sial* layer is reduced in thickness by an amount $h - x = h - 2{\cdot}4\ h/3{\cdot}4 = h/3{\cdot}4$.

It is assumed in arriving at this result that the 3·4 material does not itself become more dense during the subsidence. Whether this material be eclogite or dunite there is no evidence to suggest the possibility of any further change of facies due to increased pressure; if there were any such possibility seismic or petrological evidence should have revealed it. The only change in density that can be demonstrated is that depending on the compressibility of the material, and for our purpose that is quite negligible. Contraction by cooling need not be considered as it would be impossible under the circumstances; and expansion by heating, which would occur as the region sank, would lower the density instead of raising it.

We have, then, seriously to face a reduction in thickness of the original *sial* layer of the order $h/3{\cdot}4$ while the mass within that layer (or its equivalent if there is an interchange of material) remains constant. The reduction in thickness can thus be expressed as an increase in density. Taking the original thickness of the sial as 20 km. and different values of h, the corresponding reduced thicknesses and the respective increased densities are as follows :—

h =	0	4	8	12	16	kilometres.
Sial =	20	18·8	17·6	16·5	15·3	,,
Density =	2·7	2·87	3·06	3·28	3·53	–

With an original *sial* thickness of 30 km. we find :—

h =	0	4	8	12	16	20	kilometres.
Sial =	30	28·8	27·6	26·5	25·3	24·1	,,
Density =	2·7	2·81	2·92	3·06	3·16	3·36	–

It is immediately obvious from these figures that neither compressibility nor thermal contraction can be significant factors in whatever process may be responsible for the change of conditions. Changes of facies would go part of the way towards explaining a shallow geosyncline, but with granite and diorite as the original materials of the *sial* there is no known change that could increase the average density to more than about 2·9. The transformation of diorite into hornblende-epidote-albite rock would raise part of the layer to possibly 3·0, but there is no evidence that this could be brought about by load metamorphism alone. The difficulties cannot be evaded by altering the assumed densities within any reasonable limits. In the extreme case of the Cordilleran geosyncline, all or nearly all of the original basement of *sial* must have attained a density of 3·4 or more, or have been replaced by other material having such a density.

I can see no possible way of attempting to solve the problem here exposed, so long as the rigid limitations of a continuously cooling earth are adhered to. Even if the layer here assumed to be diorite were to be basaltic glass and were to change to eclogite, the deeper geosynclines would still remain unexplained; and, indeed, apart from the improbability of such a change, the evidence of contemporaneous vulcanism [1] is conclusively against it. Following up this clue and admitting fusion in the depths, it is clear that the removal of lighter magma from a region by lateral migration within the crust, accompanied by the lateral introduction of heavier material from greater depths, would lead to subsidence, and that later consolidation might then accentuate the depression.[2] But such fusion, initial or subsequent, implies at least an equal proportion of fusion in the columns beneath the adjoining borderlands; otherwise the geosynclinal area would become relatively uplifted by the implied expansion. This implication of regional fusion is, however, not in accordance with the hypothesis of continuous cooling.

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[1] R. A. Daly, *Igneous Rocks and their Origin*, 1914, p. 186.

[2] A process of this type might explain the remarkable depressed region that lies across Greenland in apparent continuation with the Icelandic Ridge. See L. Koch, *Journ. Geol.*, 1923, pp. 28 and 59.

The great Cordilleran geosyncline provides a certain amount of evidence in favour of the process suggested. In the late Carboniferous or early Permian a low arch began to appear within the geosyncline, dividing it into two. Vulcanism broke out on the rising geanticline and continued intermittently until the Jurassic when enormous batholiths of granite, granodiorite and diorite invaded the region. Meanwhile the lateral geosynclines continued to sink.

There is another possible method of initiating geosynclines which is, however, equally at variance with the demands of a continuously contracting earth. This method involves thinning of the original *sial* layer by tension with compensatory upward surging of 3·4 material from the depths to maintain isostatic equilibrium, the whole process leading to a downward sag of the surface. The lower layers would probably stretch by flowage and recrystallization, producing in place of diorite a schistose facies of greater density. The upper levels would give way by normal faulting. There is some evidence that such stretching may have actually occurred. In the west of North Carolina the bordering thrust faults of the Appalachians have brought up slabs of the rocks which were formerly deeply buried beneath the Appalachian geosyncline. Writing of these, Keith[1] observes that they "have been stretched and sheared along countless planes which approximate to the horizontal over large areas. The amount of actual horizontal motion as determined by the elongation of crystals is as great as 10 to 1". Unfortunately it is not indicated how this structure has been distinguished from similar structures which may have been subsequently produced during the thrusting itself, and consequently this evidence cannot be accepted as indubitable.

Dr. A. C. Lawson has attempted to explain oceanic deeps by stretching.[2] He takes the layer that is stretched to be originally 60 miles thick, to have a density of 3·0 and to be underlain by material having a density of 3·3. On these assumptions the necessary thinning of the crust amounts to 19 miles. None of the figures, however, are supported in any way by seismic evidence and the more probable figures adopted in this paper would make the requisite stretching so great that the layer of *sial* would locally thin out altogether. This could be most readily accomplished by fissuring, and the injection into the fissures of peridotite magma from below. Subsequent consolidation would then drag down the injected belt to just such depths as require to be explained.

Injection of peridotite magma into the basement rocks of a geosyncline would similarly make possible a further subsidence. Contemporary vulcanism of the ordinary kind (basaltic, andesitic, and spilitic) merely changes the level of materials already in the geosynclinal column, and in general at the cost of an overall reduction in density. This reduction, however, may be balanced or overcome by metamorphism in depth. The chief significance of contemporary vulcanism is its implication of regional fusion, reference to which has already been made in connexion with initial conditions. Fusion beneath the geosyncline alone would bring the subsidence to an end on account of the local expansion involved.

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[1] A. Keith, *Bull. Geol. Soc. Am.*, vol. xxxiv, 1923, p. 372.

[2] *Bull. Nat. Research Council*, U.S.A., No. 46, 1924, p. 19.

Summing up, we may conclude that the only known causes competent to produce geosynclines in which the original floor has subsided to great depths are (*a*) migration of light magmas from the geosynclinal column into the bordering regions; and (*b*) thinning of the original *sial* layer by stretching; in each case accompanied by the compensatory inflow of heavy material from greater depths. Subsidiary to these causes and dependent upon them is the increase of density of the lighter rocks by contact, load, or dynamic metamorphism. Any other contributary causes are just as likely to be operative in neighbouring columns as in the depressed column. Both of the processes here advocated as worthy of recognition demand widespread fusion; in the one case in the *sial* rocks themselves; in the other of the deeper seated materials (in order to make possible the stretching of the *sial*). Both are therefore completely at variance with the limitations of a continuously cooling earth, but both are in accordance with any alternative hypothesis that permits fusion to occur on a regional scale. The bearing on petrogenesis of the conceptions developed above is briefly introduced in the final section of this paper.

4. VOLCANIC PHENOMENA.

Dr. Jeffreys frankly admits that the hypothesis which I am criticizing fails to explain vulcanism, but he suggests that the recent work of Dr. A. L. Day and his colleagues on some of the causes of modern volcanic activity[1] goes far to provide an explanation which is independent of radioactive sources of heat. The concluding sentences of the inspiring address which Dr. Day delivered at the celebration of the Centenary of the Franklin Institute summarize a long and consistently sustained argument: "Through all of these studies our conclusion seems to stand fast wherever it is applied, namely, that the outstanding factor in determining the character of modern vulcanism is the gas content of the crystallizing magma. If this be mainly of steam released in a closed chamber, as at Lassen Peak, then only steam explosions are to be expected as the surface manifestations of the crystallization of the magma below; if to the steam are added such chemically active gases as chlorine, sulphur, hydrogen and the hydrocarbons, then chemical reaction between these will be a sufficient cause of higher temperatures, and lava flows of the character well known at Vesuvius, Stromboli, or Kilauea."

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[1] A. L. Day, *Journ. Franklin Inst.*, Aug., 1925, p. 161 (Centenary Address). A. L. Day and E. T. Allen, *Carn. Inst. Wash. Pub.*, No. 360, 1925 (Lassen Peak). G. W. Morey, *Journ. Wash. Acad. Sci.*, xii, 1922, p. 219.

This brilliant elucidation of the superficial phenomena of present-day volcanoes cannot fail to be welcomed with admiration by all geologists, but it nevertheless remains certain that "the crystallization of the magma below" demands the pre-existence of a magma to crystallize, and it is just there that the ultimate problem still lies. Dr. Day himself points out that conditions must have been very different when the great plateau basalts of the Deccan, the Snake River basin and other regions were poured out from crustal rifts. No alternative explanation of the origin of deep-seated magmas has yet been suggested which is so generally applicable as that based on the radioactivity of the rocks.

The particular difficulty that has to be met by Dr. Jeffreys is that the downward distribution of radioactivity adopted (limited by the assumed condition of continuous cooling) leads to a downward distribution of temperature which is inconsistent with the production of magmas such as have given rise to the great spreads of plateau basalts that are known in every continent. If the assumed distribution of radioactive elements be correct, then the "basaltic layer" must be at a temperature far too low to permit the initiation of igneous activity within it by any process consistent with the hypothesis. If, on the other hand, the material extends down to a considerable depth, the distribution of radioactivity necessarily involves the accumulation of heat and the gradual genesis of magma. Igneous activity then becomes the mechanism by which the excess of energy is transmitted towards the surface. But in this case the restrictions imposed by the hypothesis of continuous cooling have been fatally exceeded.

Dr. Jeffreys thinks the argument from vulcanism is inadequate to justify the abandonment of the hypothesis, and, as an illustration of a parallel case, he cites the historical fact that astronomers did not abandon the law of gravitation because it failed to explain the whole of the motion of the perihelion of Mercury. Apart altogether from the disproportion of the example, there is a fundamental difference. The theory of relativity has led to an explanation of the anomalous movements of Mercury without in any way interfering with the correspondence between fact and theory that had been already achieved on the basis of Newton's approximate law. Here, however, the introduction of sufficient heat to generate magmas on the scale and in the variety disclosed by geological history completely upsets the hypothesis of continuous cooling, whether the heat be of radioactive origin or not. Magmas have demonstrably penetrated the crust again and again, and for this reason alone cooling cannot have gone on uninterruptedly for

1,600 million years; it has been repeatedly reversed and renewed. By ignoring the phases of igneous activity which it cannot explain, the hypothesis of continuous cooling is clearly dealing, not with the real earth, but with an imaginary earth in which no igneous activity has occurred since the earliest ages, except possibly beneath folded mountain regions where the *sial* has been thickened by compression.

5. Mountain Building by Compression.

The particular form of the thermal contraction theory of mountain formation which has been worked out by Jeffreys is claimed as the most notable success of the hypothesis of a continuously cooling earth. The estimate of the reduction of the earth's surface during 1,600 million years of cooling (with an exponential falling off of radioactive matter in depth) is given as about 4·2 million sq. km. The actual reduction to be explained for Mesozoic and Tertiary time alone amounts, according to the figures given by Jeffreys, to about 1·7 million sq. km.[1] More recent work tends in the direction of increasing both estimates, but as they stand they will serve well enough as a test of the theory.

Measured by the reduction of the earth's surface the compression due to cooling is proportional to the square root of the time since solidification. It is easy to calculate that in a cooling earth 1,600 million years old 35 per cent of the total compression would be accomplished during the first 200 million years, and only 6·5 per cent during the last 200 million years. That is to say, the theory provides a reduction of surface since the close of the Palaeozoic of only 0·26 million sq. km., whereas the amount to be explained is 1·7 million sq. km., more than six times as much.

If we agree with Jeffreys that a rough correspondence in order of magnitude is the most that can be expected, this criticism may not be as damaging as it seems. Let us grant to the theory all the compression it seeks to provide, and assume for the sake of further criticism that 6·5 per cent of the total compression does give a reduction in area of 1·7 million sq. km. In this case similar phenomena—implying mountains comparable in their degree of compression to those of the Alpine-Himalayan and Circum-Pacific systems—should have occurred about fifteen times during the earth's history. No more than six such revolutions are generally admitted, three in post-Cambrian time and three in Pre-Cambrian time. There may, however, have been five in the Pre-Cambrian. Yet the distribution in time of the fifteen revolutions deduced from the theory gives twelve in the Pre-Cambrian.

The intervals between these hypothetical revolutions are naturally shortest at the beginning and longest at the end, the range being from 7 million years to 200 million years. The intervals between the actual revolutions, as measured by the lead-ratios of minerals from associated intrusions, are roughly of the order of 150–300 million years.[1]

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[1] *The Earth*, 1924, pp. 135–6.

The approximate equality of interval suggests that the thermal contraction theory could make out a better case if cooling after each great revolution were allowed to begin afresh from conditions not very different from the initial conditions; that is, provided that the ascent of magma from below has periodically restored the initial high temperatures near the surface. In each 200 million years the reduction of surface would then be about 1·4 million sq. km (35 per cent of 4·2 million sq. km.), which closely approaches the 1·7 million sq. km. to be explained. In addition there would be contraction not only from higher to lower temperatures, but also from a fluid to a solid state. In some such form as this a thermal contraction mechanism is not to be despised—but what has become of the hypothesis of a continuously cooling earth?

Another objection to the contraction theory as developed by Jeffreys depends on the fact that it requires a shallow level of no strain at the beginning, becoming gradually deeper as cooling proceeds, the present hypothetical depth being of the order 150 km. Thus the early mountain systems would be superficial structures involving overthrusting, whereas the later mountains would be thick-shelled structures involving deep folding with little overthrusting or none.[2] Again the consequences of the theory fail to match the facts.

The shortening across the Alps is now conservatively estimated by Heim as 200–300 km., and it is well known that some geologists prefer far more startling figures. But even the minimum estimate implies that the older features of Africa and Europe were formerly at least 200 km. further apart. This conclusion implies a bodily shearing of one continent or the other, or of both, over a substratum, and it is difficult to conceive how radial contraction in a solid cooling earth could be transformed into a lateral movement of so concentrated and extensive an amplitude. But when the compression is distributed through a rigid layer 150 km. thick, from zero at the bottom to a maximum at the top, a shearing mechanism around a great circle of the globe which would give shallow overthrusts such as those of the Alps becomes unthinkable. It may be granted that the lateral movement of one part of the crust relative to another still lacks a physical explanation on any hypothesis, but it is abundantly clear that one which allows periodically for extensive lubrication by magmas has an immense advantage that is denied to the hypothesis of a continuously cooling earth.

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[1] For a summary of recent data see A. Holmes, *The Age of the Earth*, Benn's Sixpenny Library, No. 102, 1927; and A. Holmes and R. W. Lawson, *Am. Journ. Sci.*, April, 1927, p. 339.

[2] C. K. Leith, *Structural Geology*, 1923, pp. 195–9.

6. RIVAL HYPOTHESES OF THE COOLING OF THE EARTH.

If we agree, as I think we must,

(*a*) that the hypothesis of an earth which has cooled continuously for 1,600 million years is shown, both by its consequences and its lack of consequences to be no longer tenable;

(*b*) that nevertheless the earth *has* cooled down from an initially molten state; and

(*c*) that cooling has taken place at certain stages in the earth's history by the ascent of magma and its consolidation at or near the surface;

then we may proceed at once to an inevitable deduction: *The loss of heat from the earth must be a discontinuous process.* Such a process would result from the conception embodied in the hypothesis of magmatic cycles,[1] according to which the excess heat generated within the earth by the radioactive elements is accumulated for a time in the formation of magmas, and afterwards discharged by the ascent of the magmas to higher levels and their ultimate extinction by relatively rapid cooling.

Jeffreys denies that an alternating process of this type can be deduced from the premises, and considers that, granting the latter, a steady state would be arrived at. I am quite prepared to admit that the new theory has not yet been satisfactorily expressed from the physical point of view; but I am not prepared to admit that a magma, self-heated by its radioactive contents, can reach a level at which thermal equilibrium is theoretically established without ultimately working its way beyond that level into the higher regions of more rapid cooling. This is apparently the crux of the problem. No laboratory experiment such as I am invited to devise, could hope to reproduce either the right proportions of physical quantities or the varied resources of a regional magma.[2] The possibility of permanent equilibrium is dependent on the mathematical assumptions of perfectly symmetrical conditions, of a uniform magma, and of a homogeneous roof composed of a single component. The average ideal, isolated and restricted conditions embodied in the mathematical treatment have no counterpart in the actual earth. The deviations by which the local realities depart from their regional average introduce unbalancing factors into the theoretically stable situation. The assemblage of operations all going on simultaneously —denudation and deposition, magmatic processes and assimilation, earth movements, tidal effects and acceleration or retardation of the earth's rotation and possibly others of which we are still ignorant —makes it particularly hazardous to regard the problem as a purely thermal one. The consequences of each process considered alone must be modified by due reference to the reactions set up by the others. From such considerations as these it is permissible to reject Jeffreys' conclusion that there is no possibility of alternation.

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[1] GEOL. MAG., July, 1926, p. 306.

[2] For a spectacular series of proofs of this statement see J. J. Sederholm, *Bull. Com. Geol. Finlande*, No. 77, 1926.

7. THE SPILITIC SUITE: A SUGGESTION.

It is well known that the albitic rocks of the spilitic suite have throughout geological history been characteristically developed both as extrusions and intrusions in geosynclinal regions.[1] It seems likely, therefore, that the peculiar thermodynamic environment in which the geosynclines are generated is also responsible in some way for the equally peculiar suite of associated igneous rocks. The leading features of that environment appear to be, as we have seen in section 3, fusion and stretching; moreover, the materials concerned are likely to contain a much higher proportion of the common volatile fluxes water and carbon dioxide (or their constituents) than rocks which have crystallized at less profound depths.

During the course of recrystallization accompanying stretching, the effect of differential pressure is to lower the fusion point of all compounds. In general the fluid phase that can be regarded as momentarily produced in minute specks is almost immediately resolidified since it is subject only to that part of the stress system that is equivalent to a hydrostatic pressure. This pulsating process must greatly facilitate local interchanges of atoms and molecules, and an important consequence is that certain compounds will be formed that *can* remain fluid under the hydrostatic pressure and temperature of their environment. A very simple example is provided by the dissociation of calcium carbonate when it is ground by a pestle in a mortar; minute quantities of carbon dioxide are liberated and escape into the air. In the case we are considering, such fluid or volatile compounds as may be permanently formed will tend to escape if they can, as for example by moving down a pressure gradient. One method of escape would be towards any neighbouring bodies of magma in which the corresponding vapour pressure was relatively low and in which they would ultimately be dissolved. Similarly, where differential fusion[2] is proceeding at the base of a layer that is being stretched and thinned, it is easy to see that the magma newly generated is likely to be one of unusual composition. Thus there are at least two general cases: (*a*) a normal magma may have an unusual concentration of low-temperature constituents added to it; and (*b*) a newly generated magma may be in similar respects abnormal from the start, or at least in its early stages and upper portions. In each case the residual material, (*a*) the recrystallized aggregate from which the fluid phase has been drawn or expressed, and (*b*) the undissolved material which presumably sinks to lower levels, may at some later time give rise to magma with complementary peculiarities.

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[1] For recent discussions see A. K. Wells, GEOL. MAG., 1923, p. 62; P. Eskola, *Fennia*, vol. xlv, No. 19, 1925, p. 78; W. N. Benson, *Mem. Nat. Acad. Sci.*, vol. 19, No. 1, 1926.

[2] A. Holmes, GEOL. MAG., July, 1926, p. 315.

Turning from these general considerations to the specific features of magmas of the spilitic suite we find a substantial agreement among the students of these rocks that their magmas contained an unusual excess of such compounds (or their constituents) as Na_2CO_3 and Na_2SiO_3 with notable amounts of water and free silica. The mechanism suggested above seems competent to explain the formation of magmas specially enriched in these substances, either directly by a process of differential fusion or indirectly by a process of cumulative addition. It does not explain why sodium compounds should be dominantly added or differentially concentrated, to the relative exclusion of potassium analogues, but this mysterious contrast also appears in other branches of petrogenesis and is part of another problem that need not detain us here.

The suggestion that stretching and concomitant fusion are concerned both in the development of geosynclines and in the generation of spilitic magmas is, so far as I know, the only one that correlates both geosynclines and spilitic rocks with a common underlying cause: as such I put it forward as worthy of discussion.

A Note on Deglaciation in Tibet.

By F. Kingdon Ward.

MANY travellers in Western China have remarked the presence of ancient moraines long since severed from the glaciers which made them, of glacial lakes, ice-worn valleys, perched blocks, and other relics of glaciation. Throughout the Tibetan Marches, in the provinces of Szechuan and Yunnan, such evidence is abundant. Even on the southern face of the Himalaya, where very large glaciers exist, Hooker showed that the ice once extended over a much greater area.

What is true of Western China and of the Himalaya is as true of Tibet; of that part of it at any rate which lies on either side of the Tsangpo, where that river breaks through the Himalaya; and, indeed, applies to the whole region of the great break-through by the yoked Tibetan rivers. Probably the entire plateau is a necropolis of dead glaciers, though the evidence here is less clear, partly owing to the peculiar weathering conditions, and partly to the more obvious results of prolonged desiccation, such as the shrinkage of lakes.

In the Tsangpo valley, however, these glacial marks are plain enough, and especially so towards the knee bend, where the river forces the Assam Himalaya, at the head of the gorge. Here the snowy ranges on either bank show the process in operation, for all the glaciers of the great peaks, such as Namcha Barwa and Gyala Peri, are in active retreat. This is even more obvious on the next range to the north of the river, the Tsangpo-Salween divide.

Numerous glaciers from the two peaks just mentioned formerly entered the Tsangpo itself. No less than five, originating on Namcha Barwa, still end within 2 miles of the river, though for the most part far above the present water level. The Tsangpo valley, from the head of the gorge (lat. 29° 35′ N., long. 94° 55′ E.) for a hundred miles westwards has much the appearance of an ice-worn valley, and at the head of the gorge where the present glaciers approach most nearly to the river, are a succession of gravel terraces on both banks, which clearly are ancient moraines through which the present river has cut a passage; in other words, these Namcha Barwa glaciers once flowed right across the present river bed, and piled up moraines on the north bank, which are now many hundreds of feet above water level. To-day only one glacier from Gyala Peri on the north bank, squeezing through a steep and narrow glen, actually reaches the river. A few particular instances of glacier-worn valleys in this region may now be given.

(i) The upper valley of the Rong chu is entirely glacier made, and the village of Lunang (lat. 29° 45′ N., long. 94° 50′ E.), built on a terminal moraine, marks the ice limit. The contrast between the broad, open U-shaped valley above Lunang, which is practically all pasture land, dotted with small villages, and the narrow tortuous forested glen below, with its overlapping spurs and crashing torrent, is most marked. The total length of the main glacier was about 12 miles, and it received numerous affluents. Just above the small village of Tumbatse is a perfectly preserved median moraine, by which one ascends to the Tang La. Another excellent median moraine carries the much-used path to the Temo La, a few miles higher up the valley.

(ii) The valley above Tongkyuk (lat. 30° 0′ N., long. 94° 50′ E.) is glaciated for a distance of at least 10 miles below the pass known as the Nambu La; and the glacier must have been a big one, since it received several quite considerable glaciers from the Salween divide to the north, remnants of which may still be seen. Again we get the sharp contrast between the broad undulating pastures of the upper glaciated valley and the wooded ravine of the lower water-worn portion.

(iii) The Pasum (Trasum) Lake, which is about 20 miles round, occupies an ice-worn basin blocked by a moraine, and at least one glacier formerly flowed in at its head; as is even now true of another smaller lake we discovered, though the ice foot does not quite reach the water. The Atsa Lake on the China-Lhasa road, just north of the Tsangpo-Salween divide, has been similarly formed; and all the valleys which lead southwards from the Salween divide to the Gyamda river (a tributary of the Tsangpo) are ice-worn.

(iv) Turning to the Assam Himalaya, the Doshong La (lat. 29° 30′ N., long. 95° 0′ E.) stands at the head of an old glacier valley, as the tread and riser structure, and the planed gneiss rocks, no less than the deep water-worn V in the U-shaped floor, prove. This glacier must at one time have reached the Tsangpo, a distance of nearly 10 miles, as a huge perched block just above the river shows.

In this connexion we may note that the lowest and easiest passes are often found in connexion with the loftiest and most formidable peaks, both in the Himalaya and in Western China generally; the explanation of the apparent paradox being that the highest peaks give rise to the biggest glaciers, which, retreating, have left exposed easy passes. Thus the Doshong La, 13,500 feet, is situated within 10 miles of Namcha Barwa, 25,445 feet.

(v) The Nam La, just east of the Doshong La, is still occupied by a small glacier and snowfield, being 3,000 feet higher than the latter. But of three glaciers on the cliffs above the lake which occupies the head of the valley, not one reaches the valley proper. Formerly a combined glacier reached several miles down the valley, to join one of the still existing glaciers from Namcha Barwa. The path to the Nam La crosses several overgrown moraines, and also two small meadows surrounded by steep forest-clad slopes—obviously silted up lake beds.

Enough examples have been given to show the nature and extent of the deglaciation which has been going on round the knee-bend of the Tsangpo. All those quoted, and many more, occur within an area of less than 3,000 square miles.

It would be interesting to try and get even a rough idea of the amount of deglaciation which has taken place in this region, and what some of its effects, at least, are likely to be.

The total area of what we may call the river gorge country including parts of Eastern Tibet and Western China, between the parallels of 28° and 38° and the meridians of 91° and 101°, is about a quarter of a million square miles.

Suppose that our main valley glaciers are on the average 10 miles long by $\frac{1}{2}$ mile wide and that the ice was 200 feet thick. If we allow that from every 100 square miles, two such glaciers have completely disappeared—a very conservative estimate; then the total amount of ice removed is, in round numbers, 139 billion cubic feet. As the weight of 1 cubic foot of ice is 57·2 lb., the total weight of ice is 7,950,800,000,000,000 lb., spread over a quarter of a million square miles, or 14,197,857 tons per square mile, if the weight were evenly distributed, which of course it is not, though that does not affect the argument. This load is equivalent to about 0·50 tons per square foot of crust.

The point to notice is this. We have this immense load—and a far greater load as we shall show presently, apart from the fact that the ice itself is probably much underrated—removed from the crust of the earth over a comparatively restricted area; to wit, a quarter million square miles; and we do not load any other comparable area of the crust with it. For the load was originally ice; it is now water. As ice, it is removed from a quarter million square miles of crust; but as water it is distributed over an incomparably greater area. This ice, however, even as ice, and still more in its passage as water, has removed a vast amount of rock. This, at all events, might be supposed to have loaded the crust over a restricted area, comparable to the area from which it has been removed, and thus to have counterbalanced the denuded area with its deposit. But a little reflection will show that this is not so. Over the area which we are considering, the extreme distance between the remotest rivers which have been ceaselessly carrying away this water and mud, is little more than 500 miles; and the great breach in the rim of the plateau, through which five of the Tibetan rivers pour down from the roof of the world, is only 200 miles wide.

But the mouths of these rivers, where the silt is deposited, are far apart. The two nearest—the Tsangpo (Brahmaputra) and the Irrawaddy—are 500 miles apart; while the Yang-tze mouth is separated from the Mekong by 1,800 miles of sea. Thus even the silt from one quarter million square miles is strewn over several thousand linear miles of ocean floor, from the Bay of Bengal to the Pacific. Without entering upon any calculations as to what that weight of silt might be, since no data are available, it will be admitted that it is considerable—probably not less than the weight of ice which removed it.

It seems to us, therefore, that any consideration of the structure and origin of this remarkable region requires some notice of the facts stated above; the concentration of an immense load over a restricted area, and its ultimate dissipation. Over this area there seems to be no simple relationship between load removed and load deposited; and compensation of the crust, in order to maintain isostatic equilibrium, must have been achieved by other means.

Into the further effects of this deglaciation we need not go here, beyond pointing out broadly a few of the changes which have been brought about. Each opens up a new subject.

These changes appear to the writer to have been, briefly:—

(i) A general lowering of temperature, due to the immense amount of heat absorbed to melt the ice.

(ii) A clearer atmosphere and lessened rainfall, due to decreased condensation.

(iii) The freeing of large areas for colonization, first by plants and later, of course, by man.

It may be that with the rise of the crust in proportion to the removal of load (according to the principle of isostasy), and the consequent deficiency of matter beneath this great crustal bulge, the rivers of Eastern Tibet have been better able to dig themselves in, while working in less dense material.

REVIEWS.

Revision of the Jurassic Cephalopod Fauna of Kachh (Cutch). By L. F. Spath, D.Sc. Mem. Geol. Surv. India, Palaeontologia Indica, New Series, Vol. IX, Mem. No. 2, 1927. pp. 1–72, pls. i–vii. Price, Rs 4–12, or 8*s*.

THE Jurassic Cephalopoda of Kachh described by J. de C. Sowerby (in Grant, *Trans. Geol. Soc.*, ser. 2, vol. v, 1840) and Waagen (*Pal. Indica*, series IX, vol. i, 1893–6), have been generally misinterpreted, owing chiefly to bad drawing in Sowerby's paper and faulty restoration in the much more important and widely quoted monograph of Waagen. Dr. Spath has re-examined the types of Sowerby and Waagen, and is performing an essential and valuable service by refiguring some of them where necessary. In this, the first instalment of a description of the Jurassic (Bathonian to Tithonian) Cephalopod fauna of Kachh, the Belemnitidae, Nautiloidea, Phylloceratidae, and Lytoceratidae alone are considered. The opportunity is taken of proposing a new classification of the post-Triassic Nautiloidea, Phylloceratidae, and Lytoceratidae, given in tabular form and discussed. The Nautiloidea are divided into 5 families and 28 genera, 16 of which are new; the Phylloceratidae into 5 subfamilies and 23 genera (7 new); the Lytoceratidae (as here restricted) into 4 subfamilies and 20 genera (16 new); some forms hitherto included in the Lytoceratidae are grouped into 9 families and 26 genera (4 new). The Kachh representatives of the Phylloceratidae include 15 species referred to 5 genera; of the Lytoceratidae, 4 species referred to 3 genera. Dr. Spath has already published a very condensed account of the Ammonite fauna of Kachh in dealing with the Blake Collection (*Pal. Indica*, N.S., vol. ix, Mem. No. 1, 1924); in the future parts of his present work one may expect diagnoses and figures of the many new genera and species there erected.

A. G. B.

The Geology of South Africa. By A. L. du Toit. pp. x + 463, with 39 plates, 64 text-figures, and a geological map. Edinburgh: Oliver and Boyd, 1926. Price 28*s*. net.

SINCE the appearance of the last editions of the well-known works by Hatch and Corstorphine on the geology of South Africa generally, and by Rogers and du Toit on that of Cape Colony, the subject has made great strides, and to one whose personal knowledge of the country dates back to 1910, the progress made is rather bewildering. Since that time there have been great developments, not only in the local geology of the Union, but very much has been done by way of correlation with other parts of Africa.

It is obvious then that there was room for another general treatise, and no one is better fitted than Dr. du Toit to carry out this gigantic task. Although some time ago he left survey geology to take up special work in connexion with irrigation, he has not by any means lost his general grasp and the faculty of taking broad views; on the contrary, it is possible that the change has even enlarged his outlook. In the leisure hours of a busy official life, he has somehow managed to produce a very large and very beautiful book, which must for a long time remain the standard work.

Among all the wealth of material here presented, it is very difficult to pick out special subjects for comment. It is hardly necessary to refer here to some of the most striking developments of African geology, such as the recent studies of the Bushveld complex and of the Vredefort Mountain Land, which are known to everybody, at least in general terms, but a word or two may be said on one or two minor and less well-known, though important points.

Twenty years ago the stratigraphical equivalence of the Malmesbury series of the Cape Province was very uncertain, and there were other formations, such as the Ibiquas and Matsap series, occupying a still more vague position. Again, it was quite uncertain whether the sandstones of Natal were representatives of the Table Mountain sandstone and what was the relation of both to the Waterberg sandstones and conglomerates of the Transvaal. Dr. Hatch maintained that the Natal sandstones were the equivalent of the Table Mountain series, and Dr. du Toit upholds this view. There is undoubtedly a marked lithological resemblance. However, the suggested correlation of these formations with the Waterberg sediments still remains somewhat doubtful, for reasons duly set forth in this book.

It may now be accepted in general terms that the Malmesbury series of the Worcester-Robertson-Ashton area is contemporaneous with the Transvaal system, by means of a roundabout correlation, through the Campbell Rand and Otavi dolomites, although Dr. du Toit avoids committing himself definitely as to the equivalence of the Cango dolomite to the other similar lithological types. The Ibiquas series is considered to be later than the Malmesbury, being separated from it by an unconformity, and corresponding to the Pretoria series of the Transvaal. On the other hand, the Matsap beds are here with some doubt linked up with the Waterberg and Umkondo systems.

When we come to the later ages the modern developments are perhaps less spectacular, since the Cape and Karroo systems were already pretty well known in the Union twenty years ago. Many important correlations with the rocks of other areas have, however, been carried out. Special mention may perhaps be made of the recognition of the wide distribution of the Bokkeveld Devonian marine fauna and the detailed reptilian zones of the Karroo. It may perhaps be suggested that Dr. du Toit glides rather lightly over his own remarkable work on the dolerites of the last-named system, and does not bring out with quite sufficient clearness the enormous magnitude of this peculiar phase of intrusive igneous action, which in volume is comparable with the vast surface-flows of the great basaltic plateau-eruptions.

As might be expected, the economic geology of South Africa receives adequate attention, not only in the general text, but in a special chapter in the form of a summary, and full recognition is given of the relation of ore-formation to igneous activity. Earliest of all are the chromite ore-bodies of Rhodesia. The principal period of mineralization accompanied the intrusion of the " old granite " especially in the north ; second only to this was that accompanying the Bushveld complex, while later episodes, possibly post-Waterberg, gave rise to the ores of Insizwa and the quartz-platinum lodes of Nylstroom. Coal, asbestos, gold, and diamonds also receive adequate recognition, as well as the innumerable minor mineral products of this wonderful country. Tin is also of increasing importance in the Bushveld area.

The book is beautifully printed, and commendably free from printer's errors. The numerous plates and figures are very well reproduced, many of the pictures being very striking examples of geological photography. The coloured geological map is necessarily somewhat generalized, owing to the small scale, but is a very good specimen of its class. It is difficult to understand how such a book, with its wealth of illustration, can be produced at the price.

R. H. R.

REPORTS AND PROCEEDINGS.

Yorkshire Geological Society.

12*th March*, 1927.

" The Carboniferous Zones in the Vale of Todmorden and Crimsworth Dean." By W. Lloyd and J. N. Stephens.

The Vale of Todmorden, including the well-known section exposed in Crimsworth Dean, became of especial interest to Yorkshire geologists as far back as 1841, when T. Brown published a description of numerous new species from the " Limestone Shales " of the Vale of Todmorden.

The primary purpose of this paper is to refer the various recorded fossil localities of this area (along with newly discovered localities) to their true stratigraphical horizon. This has been rendered comparatively simple by the application of Bisat's goniatite zones to the recent mapping by the Geological Survey, in which the authors have taken part. The exposed beds range from the top of the *Reticulatum* zone down to the upper part of the *Bisculcatum* zone.

GLASGOW GEOLOGICAL SOCIETY.

14*th April*, 1927.

"Some Geological Notes on three Districts of Northern Scotland." By A. G. Steavenson, M.A. The communication comprised three papers: 1. "The Stornaway Torridonian Outlier"; 2. "Some Foliated Granites in Western Lewis"; 3. "The Geology of the Stromness District, Orkney Islands."

The first of these dealt mainly with the conglomerate outlier at Stornaway and around Broad Bay, and gave a full account of the lithological character of the rocks and their relations to the Archaean platform on which they rest. They consist chiefly of conglomerates with subordinate reddish sandstones and mottled mudstones, and have a total thickness of not less than 5,000 feet. They are referred by Mr. Steavenson to the Torridonian. The second paper described an area in Western Lewis around Loch Roag in which occur masses of foliated granite intruded into the Archaean Gneiss. The third paper showed that in the Stromness district there occur at least four inliers of older rocks flanked by breccias and representing islands in the ancient inland sea in which the Old Red Sandstone sediments were deposited. An account of the surrounding rocks was given and an interesting record made of a lava flow at Navershaw, two-thirds of a mile E.S.E. of Stromness.

MINERALOGICAL SOCIETY.

15*th March*, 1927.

C. E. Tilley: "A melilite-spurrite-Ca_2SiO_4 assemblage from Larne (Antrim)."

This contact metamorphic assemblage together with merwinite, perovskite, wollastonite, aegirine, and other minerals occurs at the border of Cretaceous limestone and a Tertiary dolerite near Larne. The rocks give evidence of considerable interchange during metamorphism, of which a detailed account will later be presented.

Dr. G. T. Prior: "Alkaline rocks from Nimrud volcano, Armenia."

Nimrud was a centre of eruption of alkali rocks similar to those of the Rift Valley, East Africa. The lava forming the main mass of the rim and the floor of the crater is a soda-rhyolite (comendite) containing anorthoclase felspar and the soda-pyroxenes and soda-amphiboles aegirine, cossyrite, and riebeckite. More basic lavas overlying the soda-rhyolites resemble the kenytes of East Africa in containing numerous corroded phenocrysts of anorthoclase. Ordinary olivine-basalts with phenocrysts of labradorite also occur.

G. Greenwood: "Rotating crystal X-ray photographs."

The first part of the paper deals with this method of crystal analysis as used in the German laboratories, where it was studied by the author. Two substances, tetramethylammonium iodide $N(CH_3)_4I$ and tetraethylammonium iodide $N(C_2H_5)_4I$ were investigated. The unit cell of $N(CH_3)_4I$ is a tetragonal unit of dimensions, $a = 8{\cdot}05$ A° and $c = 5{\cdot}75$ A°, and the space group is either D_4^2 or V_4^3, most probably the latter. Hence the crystal class is not the holohedral one proposed by L. Vegard. The unit cell of $N(C_2H_5)_4I$ has dimensions $a = 12{\cdot}29$ A°, $c = 6{\cdot}82$ A°, when referred to the axes demanded by the scalenhedral space group V_d^5 to which the substance belongs. A smaller unit can be found, using as " a " axis half the base-diagonal; the cell then has $a = 8{\cdot}86$ A°, and $c = 6{\cdot}82$ A°. The nitrogen and the iodine atoms in both substances are crystallographically identical, but the methyl and ethyl radicles may be half of one kind and half of another. The hypothetical structures, suggested for these substances by Groth, as deduced from topic axes, are also discussed.

Dr. L. J. Spencer : " Biographical notices of mineralogists recently deceased. (Third series.) "

The average age of the forty lives described is 68 years.

CORRESPONDENCE.

KEILORITES.

Sir,—Would Mr. R. S. Allan kindly explain or supplement his letter in your May number (p. 240) ?

Is *Keilorites* intended to replace *Trachyderma* Phillips ? If so, it must have the same geno-holotype, and that cannot be *T. crassituba* Chapman. The geno-holotype of *Trachyderma* was not fixed by Phillips, and does not appear to have been selected subsequently. There are two geno-syntypes : *T. coriacea* and *T. squamosa*. Since *T. squamosa* was the first mentioned by Phillips (1848, *Mem. Geol. Surv. Gt. Brit.*, ii, pt. i, p. 230), and is more widely distributed, I hereby take it as genolectotype, and as lectoholotype of the species I fix on the specimen figured by Phillips (1848, pl. iv, fig. 3), which is in the Museum of Practical Geology (Regd. 38371).

Is *Keilorites* intended to apply only to " the Australian forms in question " and to exclude *Trachyderma* Phillips ? That, which is the straightforward interpretation of Mr. Allan's last two sentences, is correct on principles of nomenclature, but leaves *Trachyderma* Phillips as it was before.

If *Keilorites* is to be distinguished from *Trachyderma* Phillips, then the duty devolves on Mr. Allan of justifying his procedure by a diagnosis of his new genus. The only difference hinted at by Chapman is the slightly thicker and perhaps more calcified tube.

Does Mr. Allan include the Australian " *Trachyderma* cf. *squamosa* " in his *Keilorites* ? If so, does he disagree with Chapman's comparison of it to *T. squamosa* Phillips ?

F. A. Bather.

PLIOCENE DEPOSITS ON THE SOUTH DOWNS.

SIR,—May I call attention to the discovery by Mr. W. J. Lewis Abbott some years ago of Pliocene deposits on the South Downs? His paper "On the Pliocene Deposits of the South-East of England", *Proc. of the Prehistoric Soc. of East Anglia*, vol. ii, 1915–16, part ii (reference to the South Downs on pp. 182 and 186) appears to have been overlooked.

I have been in communication with Mr. Abbott on this subject, and find that he has made a collection of specimens of fossiliferous ferruginous sandstone from the top of the Downs near Beachy Head and Willingdon, in which Mr. C. P. Chatwin recognizes the fauna of the Lenham Beds. These specimens are now in the Museum of Practical Geology.

Recently, in company with Mr. S. W. Hester, I have had the opportunity of examining ferruginous sandstone in the field in the Beachy Head district. This sandstone is present in some quantity and, while largely unfossiliferous, some blocks found yielded marine fossils of Pliocene age.

This subject is under further consideration.

F. H. EDMUNDS.

HEAVY MINERAL FREQUENCIES.

SIR,—May I be permitted a few observations in reply to Mr. Stuart's letter of your March issue? Regarding Mr. Stuart's first point I would state that the Old Red Sandstone residues were mounted in their entirety, and therefore the actual heavy-mineral composition is accurately represented by the percentage-figures. It is understood, of course, that a sufficient number of representative samples must be examined and one of the chief aims of my communication was to show the remarkable general uniformity of results obtained at different horizons in the Old Red Sandstone of the West Midlands.

Referring to the connexion between variation in mineral-composition and distance from supply-source, this is well and concisely stated by Mr. S. W. Wooldridge in his letter in the February issue of this Magazine (p. 95). Mr. Wooldridge, speaking of the Diestian deposits, says: "Over a wider area a significant regional gradation of the percentages can be detected—a regular increase in the percentage of stable species in the direction of transit of the material pointing to progressive elimination of the less resistant mineral-types." The weight of heavy mineral residue per unit weight of sediment would diminish as a result of attrition with increasing distance from supply-source, but in practice the adoption of Mr. Stuart's plan of weighing the amounts of residue, though perhaps desirable as providing additional data, is not likely to be easy, chiefly because, in many sands, the weight of heavy residues is extremely small.

The main objection to Mr. Stuart's third suggestion as to the desirability of including grain-size in the percentage frequency tables would seem to be practical difficulty when dealing with large numbers of grains, say 1,000 or 1,500, in a residue. Making due allowance for Mr. Stuart's useful criticism and suggestions one must beware of over-elaboration if the general worker in geology is not to be unduly deterred by the specialist's refinements. It is certain that the latter, combined with due caution in interpreting results, will lead to interesting conclusions regarding the deposition of sediments, but the main purpose of the original communication was to show that the accurate counting and simple percentage representation of heavy minerals in sedimentary rocks, with due regard to variation in habit, size, etc., are operations easily carried out with results that are readily comparable with those obtained by others.

W. F. Fleet.